VALIDATION OF CFD CODE ANSYS CFX AGAINST EXPERIMENTS WITH SALINE SLUG MIXING PERFORMED AT THE GIDROPRESS 4-LOOP WWER-1000 TEST FACILITY

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ABSTRACT

Validation of the CFD code ANSYS CFX was performed in the frame of the experimental and analytical investigations of mixing of coolant flows with different saline concentration fulfilled in EDO "GIDROPRESS" at 4-loop test facility modeling reactor WWER-1000 with the scale 1:5.
Calculations were performed with the 3-D code complex ANSYS CFX. The objective of the analyses was the code validation with the purpose of further practical implementation.
Calculations were performed for the case of experiments with the saline slug in the pump loop seal at the RCP start-up. Unsteady 3-D fields of saline concentration were calculated for the circuit of the facility. Comparison of experimental and predicted data is presented in the paper. Results of CFD analyses demonstrated very good agreement with the experimental data.

1. INTRODUCTION

RIA accidents with the slugs of deborated coolant flow into the core are considered in the safety analysis of WWER type reactors. These slugs are formed most likely in the RCP loop seals after cessation of natural circulation. With the resumption of circulation the slug could be delivered to the core thus causing reactivity insertion.
Mixture of the slug with the rest of the coolant mitigates reactivity effects essentially. A special experimental program was carried out in EDO "GIDROPRESS" to investigate the mixture process of coolant flows containing slug with different boron concentration in the flow path upstream the core. A saline (NaCl) solution was used in the reactor model to simulate the slug behavior during the experiments.

2. PROBLEM STATEMENT

The objective of this work was validation of the code ANSYS CFX in order to justify its further application for the safety analysis of the WWER type reactors. In the frame of the TACIS project R2.02/02 pre-test calculations of the velocities, pressure and salt concentration fields in EDO GIDROPRESS' four-loop experimental facility scaled 1:5 with regard to WWER-1000 were performed in EDO "GIDROPRESS" using the code ANSYS CFX.
Calculated results of three following experiments simulating two specific areas of regimes with coolant convection are presented in this paper:
- regimes with leading role of inertia forces characterized by Strouhal criterion; experiment with one RCP activation
- regimes with leading role of gravity force characterized by Froude criterion. Two experiments with the injection of fluid with different slug densities and coolant flow corresponding to natural circulation conditions. In the first experiment the ratio of the slug density to that of the coolant was equal 1,05, in the second experiment – 1,00.

3. CALCULATED REGION ELEMENT MESH DEVELOPMENT

To create a solid model Solid Works CAD software was used. The Solid model is required at elaboration of the calculated region element mesh that is shown in Figure 1.
Because of complex geometry of the flow path, non-structured mesh was used that consists of a few structured subregions. Figures 2, 3 and 4 such subregions are shown in different colors. 3-D evaluation model of the facility was developed for the CFD simulation of the hydrodynamic processes of boron mixing. Two complexes STAR-CD and ANSYS ICEM CFD were used for mesh development. This mesh consisted of approximately 5 million control cells. In order to check the developed evaluation model test calculations were performed with the code STAR-CD.

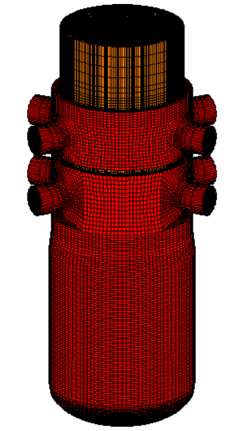

Fig.1: Calculated region element mesh

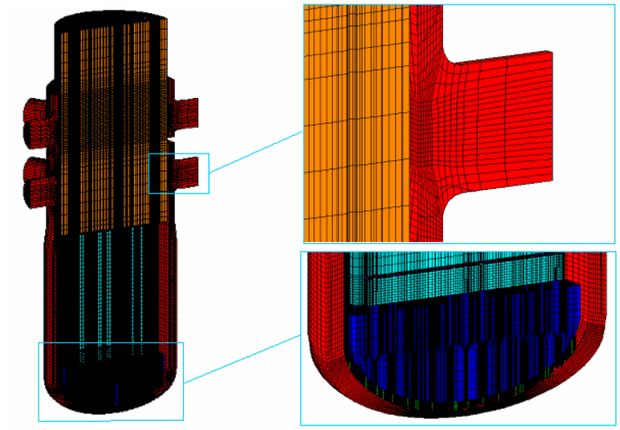

Fig.2: Inlet nozzle and support tubes

Figure 2 shows the mesh in the longitudinal cross-section of the model. The mesh is given here in more detail in the area of the inlet nozzle and in the area of the lower perforation with support tubes. Figure 3 provides the mesh of the lower part of the model in the area of perforation and in the area of measurement sensor location. Figure 4 shows the mesh behind the support tubes in the area of perforated grid and in the area of coolant evacuation. SST turbulence model was used in all calculations.

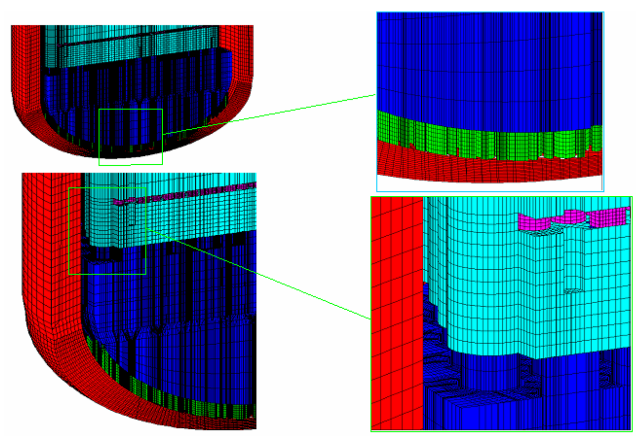

Fig.3: Part of model in the area of perforation and location of transducers

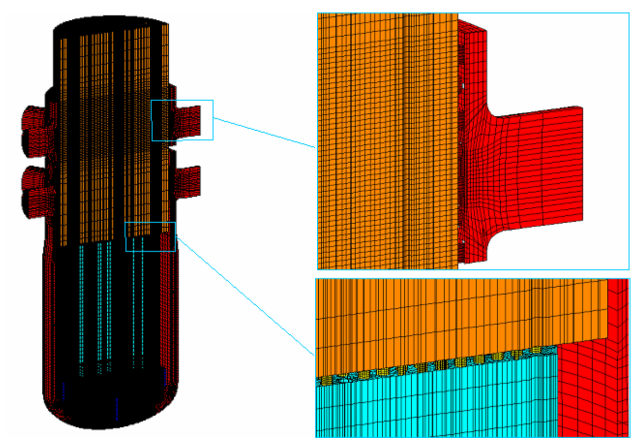

Fig.4: Perforated grid and outlet nozzle

4. EXPERIMENTS DESCRIPTION

The base of experimental facility is one-to-five scale metal model of WWER-1000 reactor wherein the geometry of the flow section of Novovoronezh NPP reactor, Unit No. 5, beginning from inlet nozzles to the core inlet is simulated.

The core is simulated partially. Instead of FA simulators and protective tube unit in the reactor model there is an «assembly». The «assembly» is a bundle consisting of 91 tubes with 14x2 mm in diameter that is assembled with the help of three spacing grids by which the pressure loss of the core and the protective tube unit is simulated. Rods with conductance measuring sensors are mounted through the model cover into these tubes.

The concentrations are measured by electronic conductivity meter "Expert-002" with the limiting admissible basic error of 2 %, brought to the upper value of the measurement sub-range.

Centrifugal pumps having the following main performances are used as circulating pumps. Each pump has a frequency-controlled drive for the control of volumetric flow. Flow rates in circulation loops are measured with the help of electromagnetic flow meters produced by YOKOGAWA Co. with an error of 0,35 % of the current value. In addition, for process purposes, the tapering orifice plates measuring flow rate with an error of 1,5 % are placed in each loop.

Initial and boundary conditions are the same for all experiments. The only exceptions are the initial slug volume and the flowrate in the Loop №4 at steady flow regime. In the initial state the testing bench is filled with water at temperature 20 ^{o}C at the atmospheric pressure. The initial concentration of salt in coolant is 0 g/kg. The pumps are not in operation at Loops 1, 2 and 3. With the help of frequency-controlled pump drive of the Loop №4 the desired curve of the flow in the loop Q_t is defined (time to reach steady flow is about 15 seconds)

$$Q_t = Q_o \cdot \left(1 - e^{-0,25 \cdot t}\right) \quad (1)$$

where:

Q_o – steady flow rate in the Loop №4;

t – time, s.

Coolant circulation in the first three loops is realized by reverse flow. The experiment stops on the basis of the symptom of salt concentration equalization in the reactor model and the circulation loops.

The calculation model for ANSYS CFX Code (Figure 5) comprises the model of reactor vessel with eight nozzles and the model of the pressure part of Loop №4. Additional coordinate system in the Figure 5 is located in the center of mass of the saline slug. Figure 6 provides sensor location in the cartogram of the channels (fuel assemblies) in the core model.

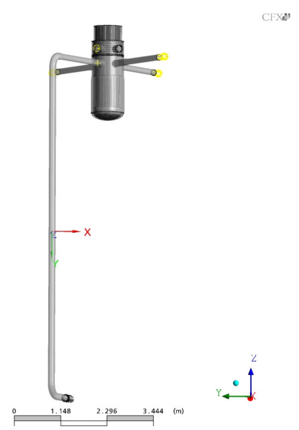

Fig. 5: Calculation model

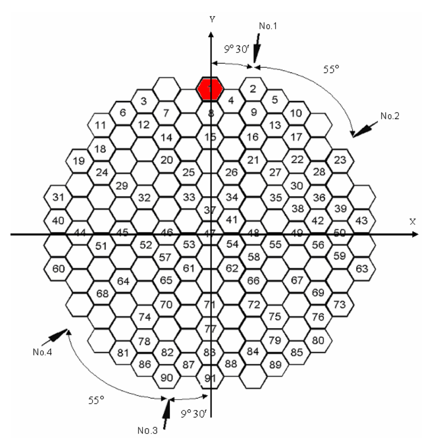

Fig. 6: Cartogram of sensor location

The boundary conditions on the flow inlet and outlet were set in accordance with the inlet and outlet nozzles of the model, respectively. In the first three models the flow inlet and outlet changed their places to model the reverse flow in the loops. The reverse flow rate was assumed to be equal to 10 % of the flow in the loop with the operating pump. Salt concentration C in the slug in Loop №4 was assumed to be equal to 1 was calculated according to the following formula:

$$C = \frac{C_i - C_0}{C_1 - C_0} \quad (2)$$

Where:

C_i – current salt concentration at the location of transducer, g/kg;

C_0 – initial concentration in the loop, g/kg;

C_1 – concentration of the solution injected into the circuit or initial slug concentration.

5. COMPARISON OF CALCULATED RESULTS WITH THE EXPERIMENTAL DATA

Evaluation model was imported into the CFD code ANSYS CFX with the help of complex ANSYS ICEM CFD. Unsteady hydrodynamic calculations for each described above experiments were performed with the CFD code ANSYS CFX to obtain the fields of salt concentrations in the facility. The time of simulation covered the period from the pump start-up to the full slug passage through the core.

A comparison of the calculation results and experimental data is given in Figures 7 – 9. Figures 7 – 9 provide relative concentration of salt in the place of sensor location. Each Figure shows two curves of salt concentration variation in time for the calculated and experimental data respectively. Sensor location is shown in red in the cartogram.

5.1 Experiment with the saline slug (initially in the loop seal, volume of 0,12 m^3) mixing in the downcomer at RCP start-up

This experiment belongs to regimes for which inertia forces characterized by Strouhal number play the leading role. RCP set at Loop №4 is started up and it reaches the nominal flowrate equal to 220 m^3/h. Slug volume in Loop №4 is 0,120 m^3.
It can be seen in Figure 7 the front of salt concentration reaches the core inlet according to the calculated data a little earlier than according to the data obtained in the experiment. The maximum advance of the calculated front in different channels can reach up to 1 second. So the passage of the front and the peak of salt concentration in different channels is also shifted by about the same value. From the results of the comparison it is impossible to single out exceeding or decrease in the maximum value of salt concentration between the calculated and experimental data relative to each other. The best agreement of the results is observed in the core centre. The maximum value of salt concentration is 0,77.
It is also seen in Figures 7 that by the end of the studies process at 40 seconds after the experiment has begun, the calculational and experimental data on salt concentration in different core channels actually coincide. From the above Figure a good coincidence of the calculational and experimental data is observed that is qualitative in the place in plan of the model cross-section and that is quantitative in salt concentration.
By the results of the analysis it is found that coolant with salt solution goes out of the inlet nozzle of Loop №4 into the downcomer to the opposite side of reactor model, at this, going downwards. Salt concentration at the core inlet first appears at the opposite side of the model to the left and to the right relative to the inlet nozzle of Loop №4 . Then it increases directly under the very inlet nozzle of Loop №4. Further on, the front of the increased salt concentration moves to the core centre and then it gradually decreases.

5.2 Experiment with the saline slug (initially in the loop seal, volume of 0,072 m^3) mixing in the downcomer at the recover of natural circulation; initial ratio of the slug and the facility coolant densities equals 1,05

This experiment belongs to regimes for which gravity forces characterized by Froude number play the leading role. RCP set at Loop №4 is started up and it reaches the nominal flowrate equal to 20 m^3/h. Slug volume in Loop №4 is 0,072 m^3.
It can be seen in Figure 8 that the front of salt concentration reaches the core inlet according to the calculated and experimental data actually simultaneously. The maximum value of salt concentration is 0,34.
According to the calculational data the main part of a higher density coolant out of the slug passes the inlet nozzle of Loop №4 and flows down directly under the nozzle itself onto the internal surface of elliptical bottom of reactor vessel model creating a steady “puddle”. "The puddle" gradually smears by a slow main flow of coolant. Because of slow flow rate through the core model the flows out of the support tube slots mix up weakly. A star of eight rays in the outlet section of support tubes can be clearly seen. So it is slightly incorrect for the given case to compare the experimental data of salt concentration obtained from the sensors and the calculational values by the singled out reference volumes.

5.3 Experiment with the saline slug (initially in the loop seal, volume of 0,072 m^3) mixing in the downcomer at the recover of natural circulation; initial ratio of the slug and the facility coolant densities equals 1,00

This experiment belongs to regimes for which gravity forces characterized by Froude number play the leading role. RCP set at Loop №4 is started up and it reaches the nominal flowrate equal to 20 m^3/h. Slug volume in Loop №4 is 0,072 m^3.
It can be seen in Figure 9 that the front of salt concentration reaches the core inlet according to the calculated data about 5–10 seconds earlier than according to the data obtained in the experiment. The maximum value of salt concentration reaches 0,49. The best coincidence of the results is observed at the core periphery.

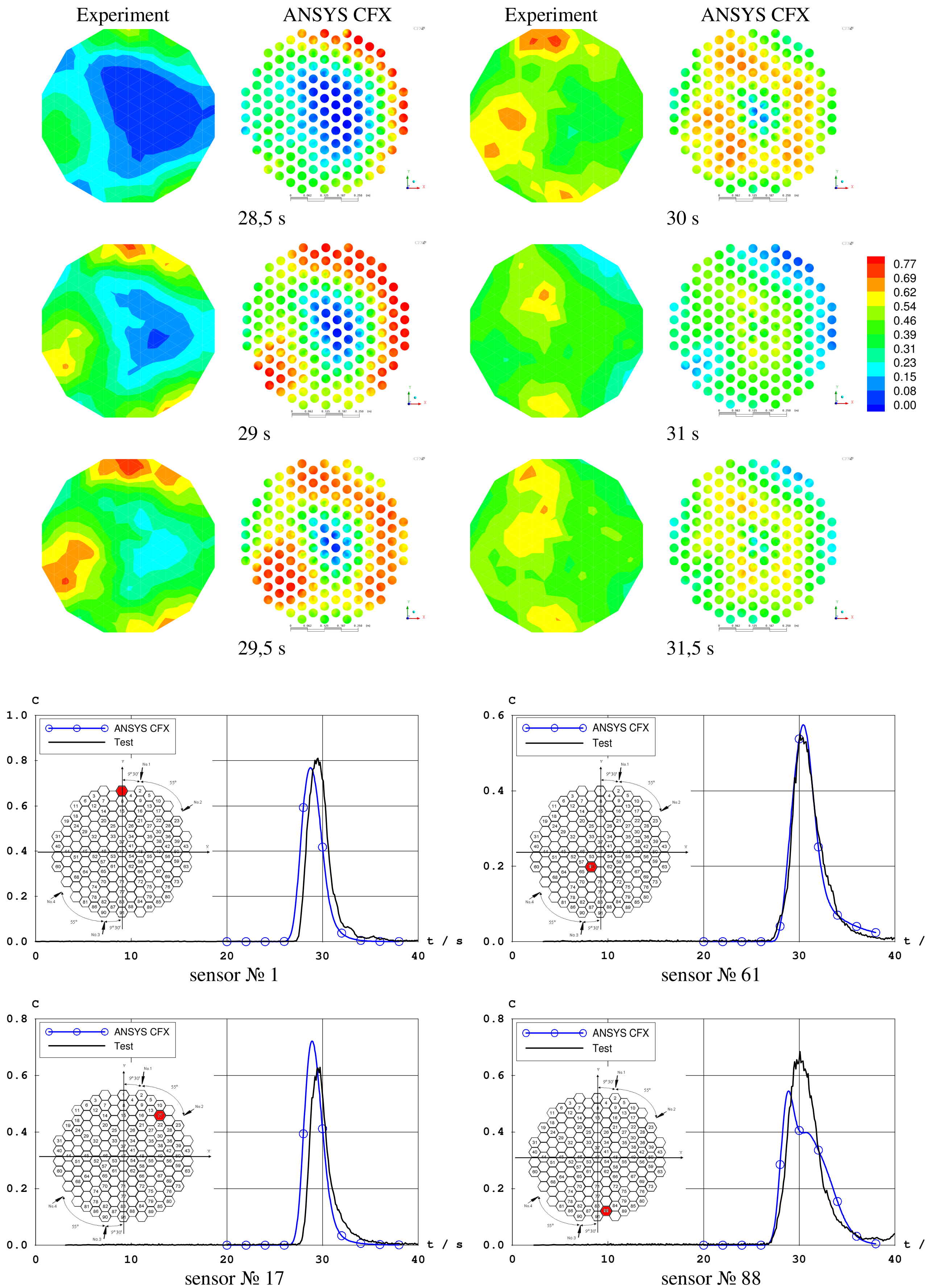

Fig. 7: Change of concentration at the core inlet

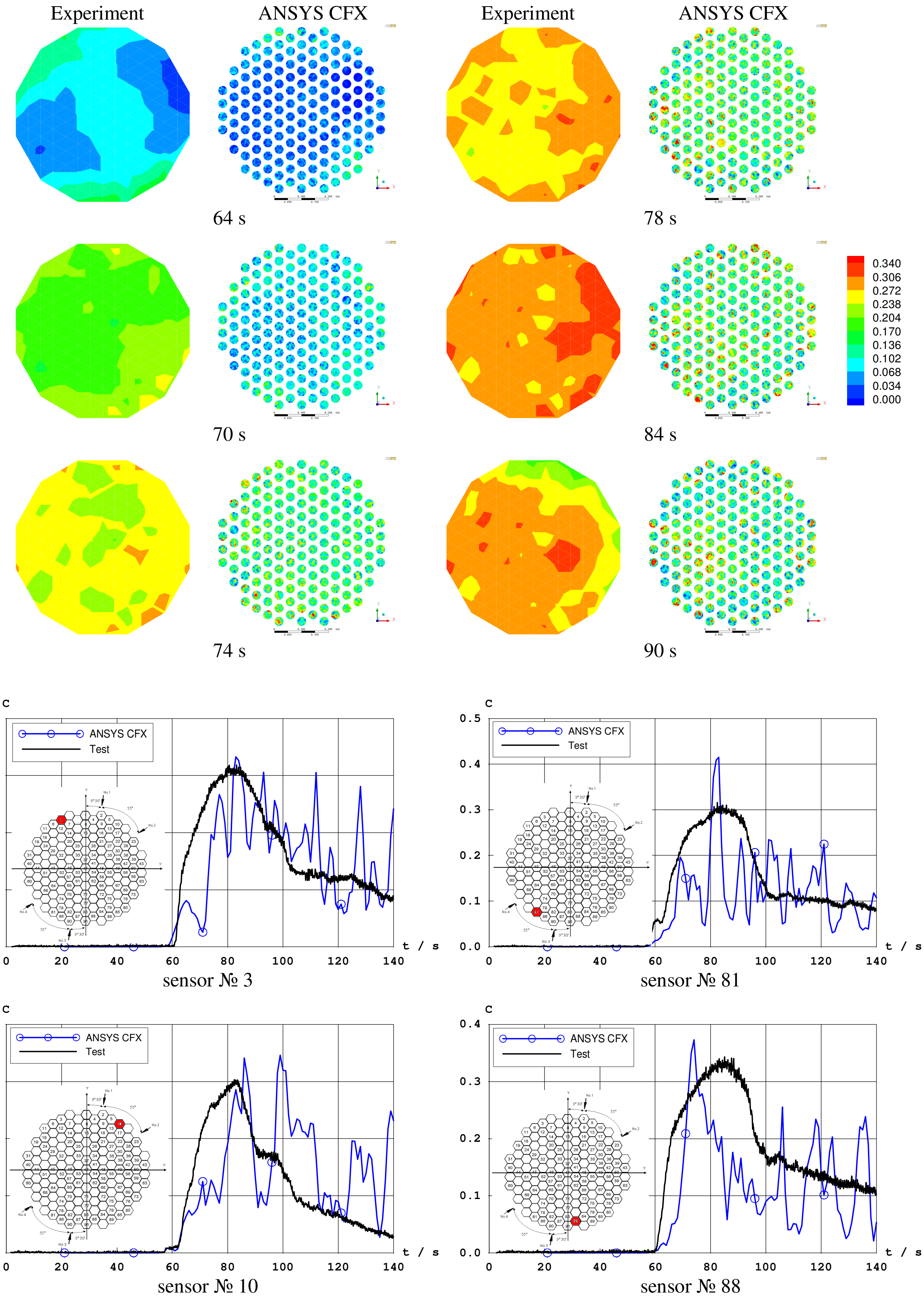

Fig. 8: Change of concentration at the core inlet

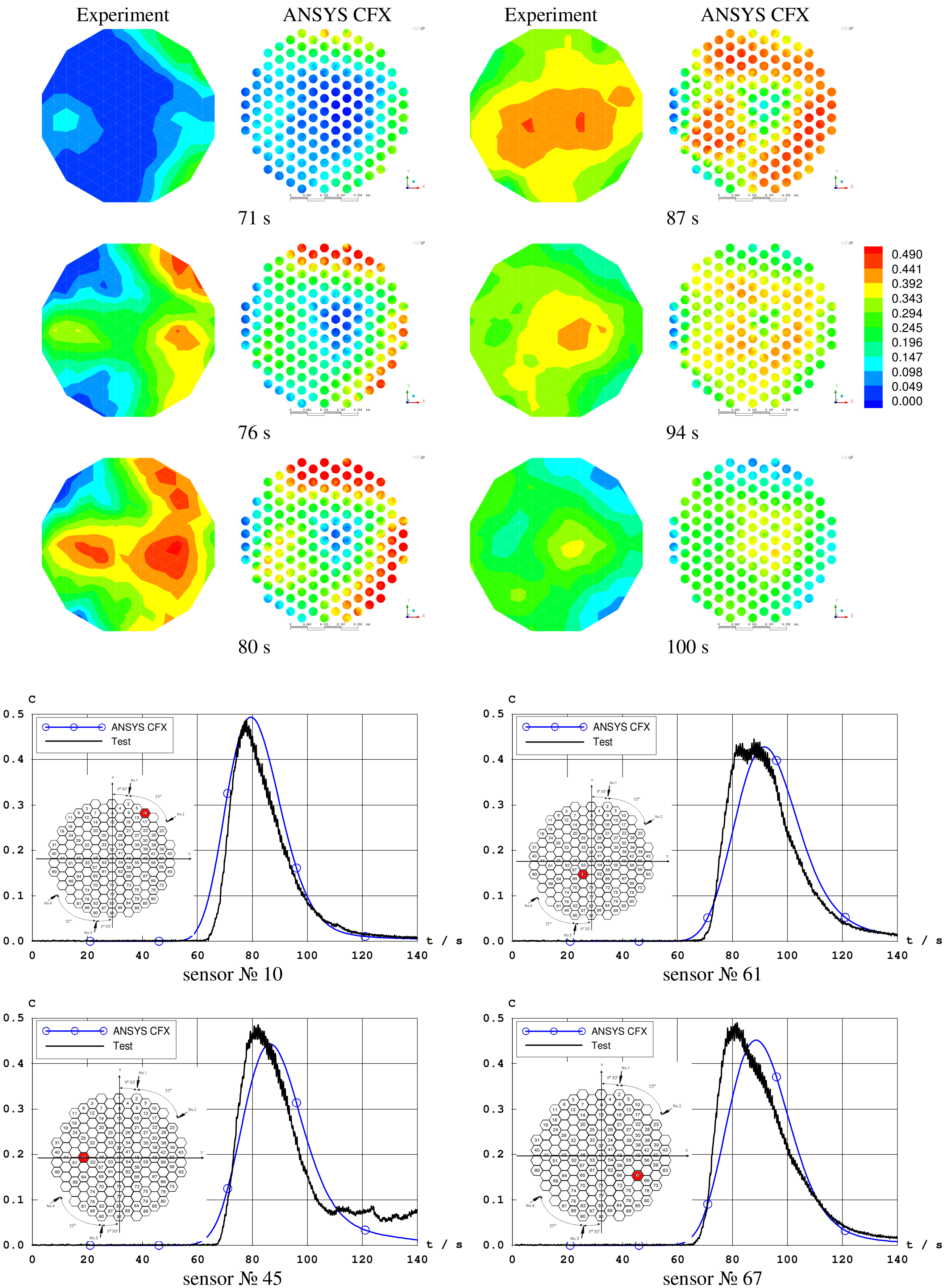

Fig. 9: Change of concentration at the core inlet

The main front of salt concentration passes the core model between 70 and 120 seconds of the experiment. First, the increase in salt concentration is observed at the core periphery opposite to left and to the right of the inlet nozzle of Loop №4 and directly under it. It occurs between 71 and 76 seconds and agrees well in place, time and the values of salt concentrations. Later, between 80 and 87 seconds the maximum values of salt concentration in the experiment move to the centre of the core inlet and in the calculational analysis they remain in their places. At this, their maximum values coincide. Only after 87 second the maximum calculated values begin moving to the core inlet. After 100 s of the experiment have passed, the calculated and experimental data again agree well in place, time and the values of salt concentrations.

6. CONCLUSION

CFD analyses of the salt concentration distribution in the test facility modeling reactor VVER-1000 was fulfilled with the complex ANSYS CFX. Numerical simulation of mixing process of coolant flows with various salt concentrations was performed and parameters of concentration fields in the whole facility were obtained. Results of CFD analyses demonstrated very good agreement with the experimental data.