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

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Abstract

One of the RIA scenarios considered in the frame of WWER reactors safety analyses is related to boron dilution phenomenon which may cause reactivity-insertion accident. Mixture of the coolant with low boron concentration with that in the reactor allows for the mitigation of the consequences. A special experimental program was carried out in EDO "GIDROPRESS" to investigate the mixture process of coolant flows with different boron concentration upstream the core. A saline (NaCl) solution was injected into the reactor model during the experiments.
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 using the code CFX. 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. Results of CFD analyses demonstrated very good agreement with the experimental data.

1. INTRODUCTION

RIA accidents with asymmetric of deborated coolant flow into the core are considered in the safety analysis of WWER type reactors. Mixture 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.
Calculated results of three experiments with various pumps in operation simulating a certain area of regimes with forced coolant convection characterized by Reynolds criterion:
- asymmetric saline injection with continuous operation of 4 pumps;
- asymmetric saline injection with continuous operation of 3 pumps;
- asymmetric saline injection with continuous operation of 2 pumps;
- asymmetric saline injection with continuous operation of 1 pump.

This set forced convection regimes is guided by hydraulic drag forces characterized by Reynolds number Re.

2. DEVELOPMENT OF THE EVALUATION MODEL

For the development the mesh of the evaluation model a solid model of the facility was used. 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. Two complexes were used to develop mesh: STAR-CD and ANSYS ICEM CFD. The size of mesh was about 4,5 million cells (Figure 1). In order to check the developed evaluation model test calculations were performed with the code STAR-CD.
In order to simulate hydrodynamic processes of saline mixing in the facility the evaluation model was developed for ANSYS CFX (Figure 2). The general model (the whole computational domain) includes the model of reactor with 8 nozzles and 4 loop models. The reactor coolant pumps are modeled by boundary conditions for the flow rate.

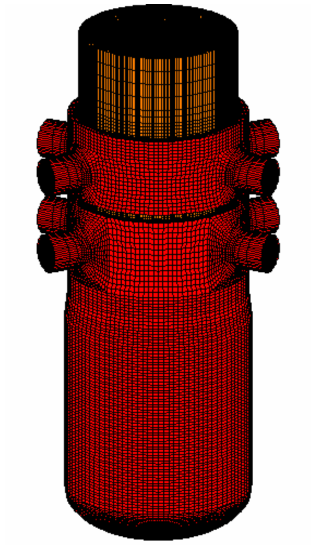

Fig.1: Calculated region element mesh

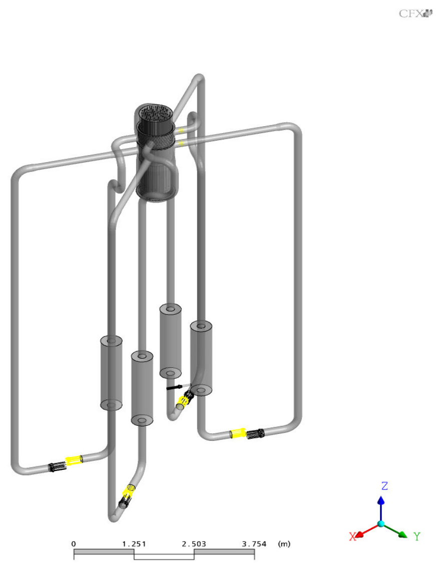

Fig. 2: Calculation model

3. EXPERIMENTS DESCRIPTION

In the initial state the experimental facility is filled with water at temperature 20 ^{o}C at the atmospheric pressure. The initial concentration of salt in coolant is 0 g/kg. Coolant flowrate in loops depends on number PCP in operation: in case of all 4 operating pumps the flowrate equals 20 m^3/h per pump, and 172 m^3/h in other cases. Salt solution is supplied into the expansion tank of Loop №2 for 60 seconds with the flowrate of 14 m^3/h and a concentration of 10 g/kg.

Coolant viscosity and density are defined for normal condition in the facility circuit and in injection line. Salt concentration in the injection is assumed to be equal to 1. Figure 3 provides sensor location in the cartogram of the channels in the core model. The results of the steady state calculation at the zero moment of time were taken for a transient calculation. Calculated time of the process covered period from the beginning of injection to achievement of equilibrium salt concentration in the facility. SST turbulence model was used in all calculations.

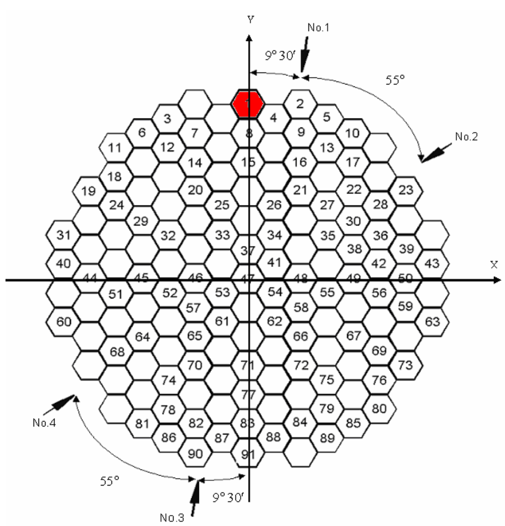

Fig. 3: Cartogram of sensor location

4. COMPARISON OF CALCULATED RESULTS WITH THE EXPERIMENTAL DATA

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.

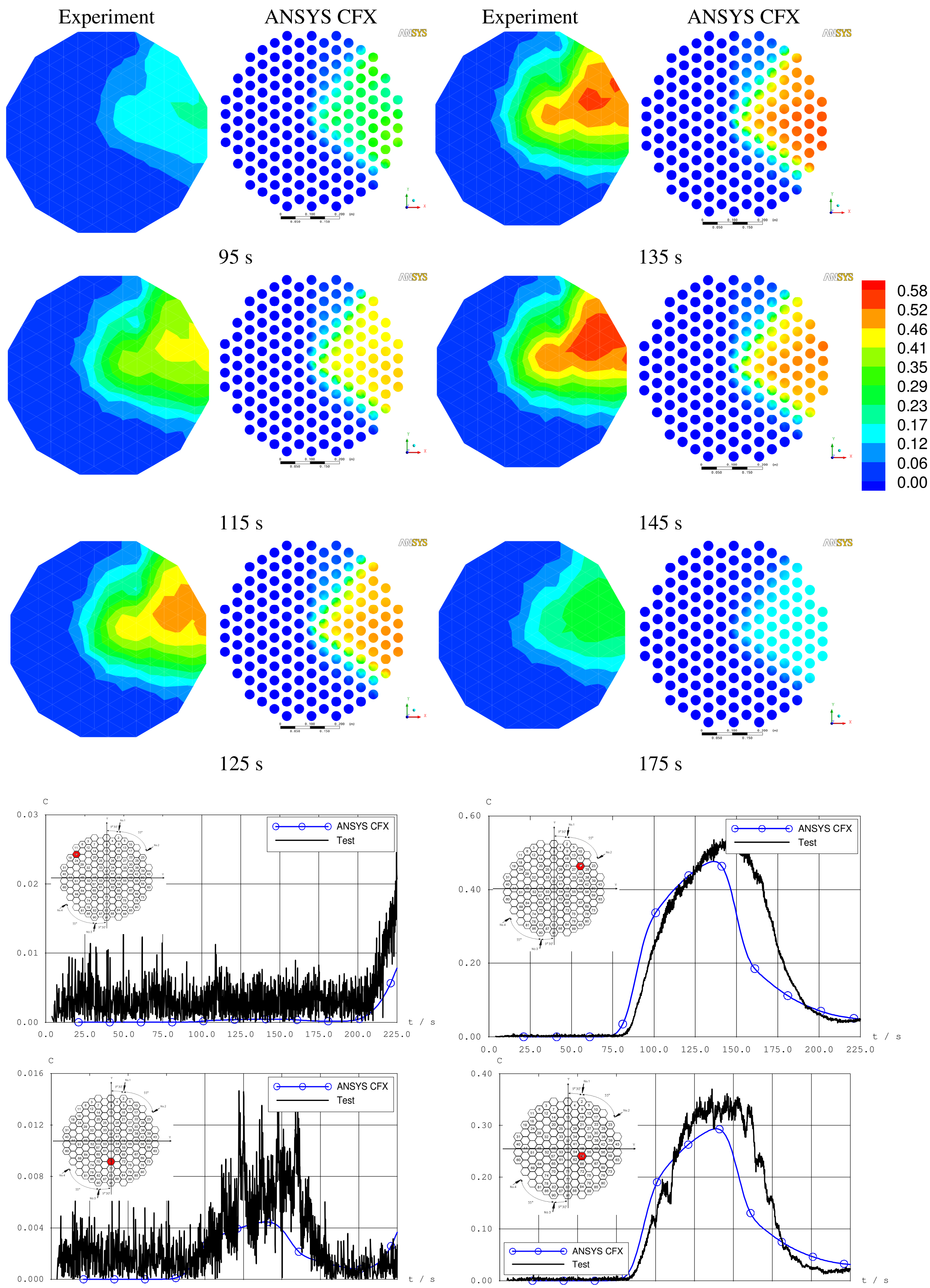

Fig. 4: Change of concentration at the core inlet

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.

4.1 Experiment with the asymmetric saline injection at continuous operation of 4 pumps

A comparison of the calculation results and experimental data is given in Figure 4. Figure 4 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.
It is shown in the Figure 4 that according to experimental data the front of salt concentration comes up to the entrance to core approximately at the 80-th second from the beginning of experiment. Maximum value of salt concentration amounts to 0,58. The front of salt concentration passed the core only once during the time of simulation due to small coolant flowrate, which is approximately 8,5 times less than the nominal one. Results of calculation show that the coolant with saline from the Loop №2 flows down and shifts left in downcomer. Comparison with the experimental data shows that the predicted flow shift from the axes of the nozzle of Loop №2 is practically the same as in experiment. At the same time the salt concentration from Loop №2 at the entrance to the core forms a sector with smeared edges and the angle of about 90^o.

Then this sector is displaced a little towards the center of the core in experiment while in calculation it is not displaced. At the same time location of maximal concentrations (left to the axis of Loop №2) coincide in calculation and in experiment. That's why one can conclude that the mixing process is described quantitatively and qualitatively well in calculations, and the area of interaction of mixing streams is somewhat different.

4.2 Experiment with the asymmetric saline injection at continuous operation of 3 pumps

Three circulation pumps are in operation that provide coolant flow rate of 172 m^3/h in the loops. The pump is Loop №3 does not operate. In Loop №3 the flow inlet and outlet were switched over to model the reverse flow. The reverse flow rate was assumed equal to 10 % of the flow in the loops with operating pumps.
A comparison of the calculation results and experimental data is given in Figure 5. Figure 5 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.
It can be seen in Figures 5 that according to experimental data the front of salt concentration reaches the core inlet within the interval from 30 to 50 seconds after the process begins. The maximum value of salt concentration does not exceed 0,16. For the period of the calculational analysis the salt concentration front has passed the core seven times. According to the calculational data coolant with the salt solution goes downwards out of Loop №2 inlet nozzle and moves to the left If we compare the calculational and experimental data, it can be seen that the calculated movement of the flow to the left with respect to the inlet nozzle coincides. At this, a sector is cut out at the core inlet that belongs to Loop №2 with salt concentration and with opening angle of about 120 degrees, smeared on the boundaries. If we make a comparison this opening angle in the experiment is slighter larger, and in the absolute value of salt concentration it differs by about the value of 0,02.

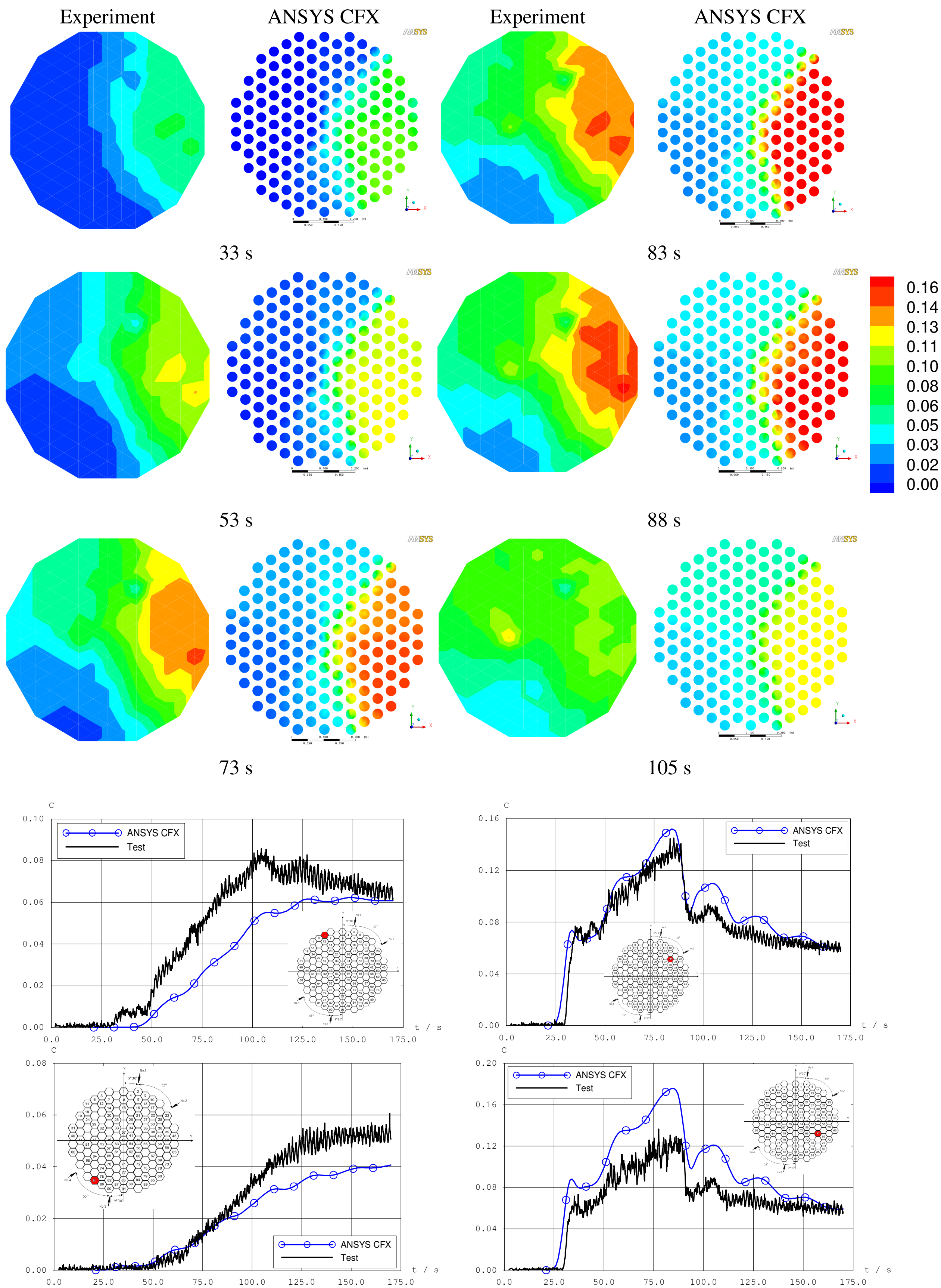

Fig. 5: Change of concentration at the core inlet

Further on, both in the experiment and in the calculation the opening angle of this sector increases to the right with respect to the inlet nozzle of Loop №2. But in the calculational analysis the absolute values of salt concentration in this place are less than the experimental ones by 0,02. At this, the place of the maximum concentrations of salt both in the calculational analysis and experimental study remain in their places to the left of the inlet nozzle. So it can be said that the process of flow mixing is described qualitatively correctly but with slightly differing absolute values of salt concentration. It is also confirmed by the data of Figure 5, where the dynamics is presented of the final stage of the experiment.
On comparing the obtained data the main discrepancy in the calculation and experiment in time and in the values of concentrations can be attributed to a slightly incorrect determination of the coolant distribution sector shift with respect to the inlet nozzle of Loop №2 on the right.

4.3 Experiment with the asymmetric saline injection at continuous operation of 2 pumps

Two circulation pumps are in operation in Loops №1 and №2 that provide coolant flow rate of 172 m^3/h in the loops. The pumps of Loops №3 and №4 do not operate. In Loops №3 and №4 the flow inlet and outlet were switched over to model the reverse flow. The reverse flowrate was assumed equal to 10 % of the flow in the loops with operating pumps.
A comparison of the calculation results and experimental data is given in Figure 6. Figure 6 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.
It can be seen in Figure 6 that according to experimental data the front of salt concentration reaches the core inlet at about 30 second of the process. The maximum value of salt concentration does not exceed 0,15. For the period of the calculational analysis the salt concentration front has passed the core six times. According to the calculational data, coolant with the salt solution goes downwards out of Loop №2 inlet nozzle and moves to the left. If we compare the calculational and experimental data, it can be seen that the calculated movement of the flow to the left with respect to the inlet nozzle coincides. But the sector itself is turned about 30 degrees more to the left than in the experiment. At this, at the core inlet a sector is cut out that belongs to Loop №2 with salt concentration and the opening angle of about 180 degrees that is smeared over the edges which fully coincides with the experiment.
Further on, both in the experiment and in the calculation as the front passes another time salt concentration is increase by the same value in the singled out sector. So, a conclusion can be made that the process of flow mixing is described qualitatively and quantitatively correctly but with differing angle of shift for the sector of increased salt concentration. It is also corroborated by the data in Figure 6, where the dynamics of the final stage of the experiment is presented.

4.4 Experiment with the asymmetric saline injection at continuous operation of 1 pump

One circulation pump is in operation in Loop №2 that provides coolant flow rate of 172 m^3/h. The pumps of Loops №1, №3 and №4 do not operate. In Loops №1, №3 and №4 the flow inlet and outlet were switched over to model the reverse flow. The reverse flowrate was assumed equal to 10 % of the flow in the loops with operating pumps.
A comparison of the calculation results and experimental data is given in Figure 7. Figure 7 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.
It can be seen in Figure 7 that according to experimental data the front of salt concentration reaches the core inlet at 35 second after the process has begun. The maximum value of salt concentration does not exceed 0,14. For the period of the calculational analysis the salt concentration front has passed the core two times. If we compare the calculational and experimental data, it is seen that they actually coincide. The only minor difference is in the fact that the calculational value of the arrival of the first front of salt concentration at the core inlet occurs somewhat earlier than the experimental value. It occurs because in the calculation an increase to the nominal value of the flowrate of the injected salt solution takes place instantaneously and in the experiment for about 5 seconds.

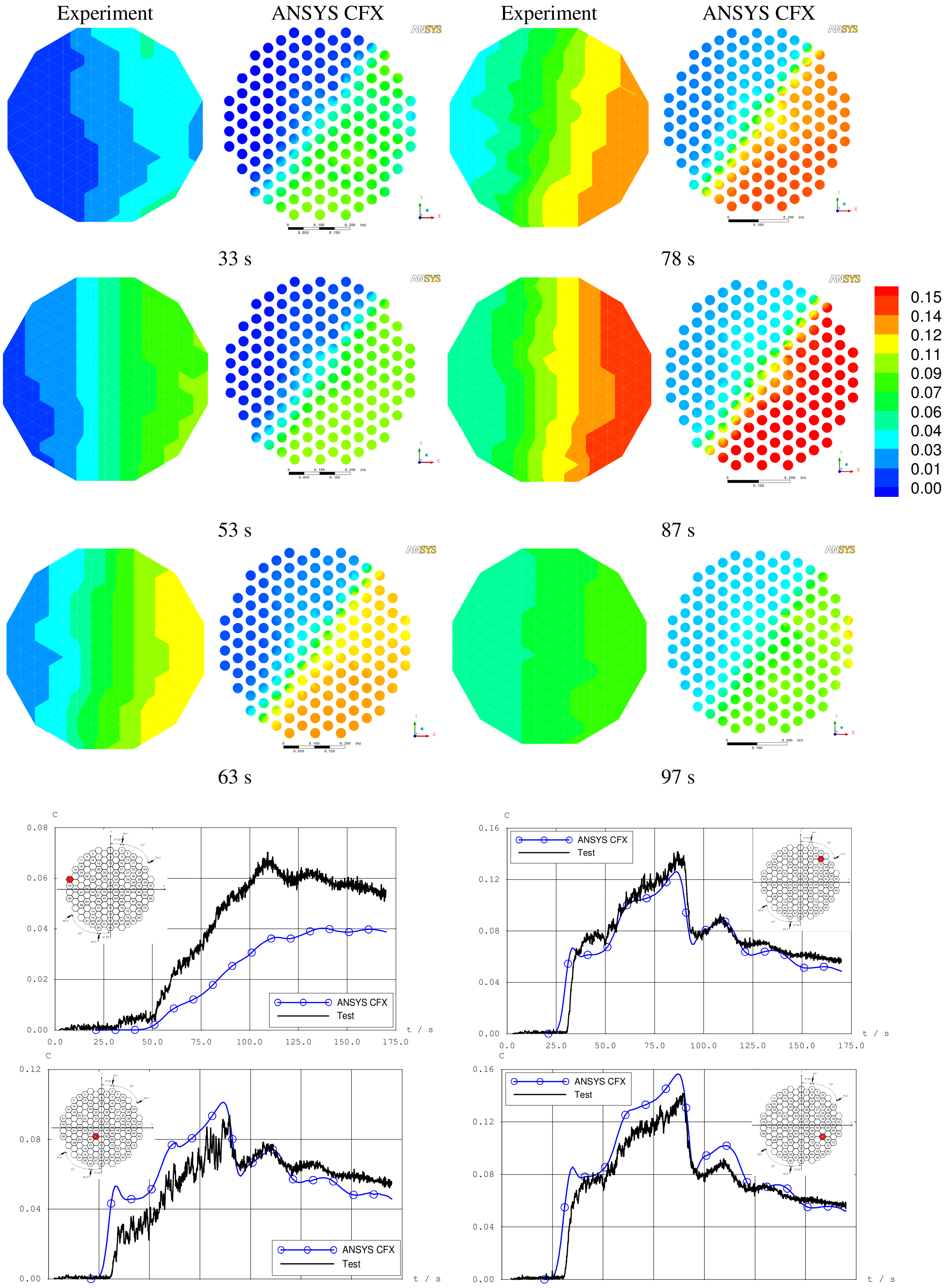

Fig. 6: Change of concentration at the core inlet

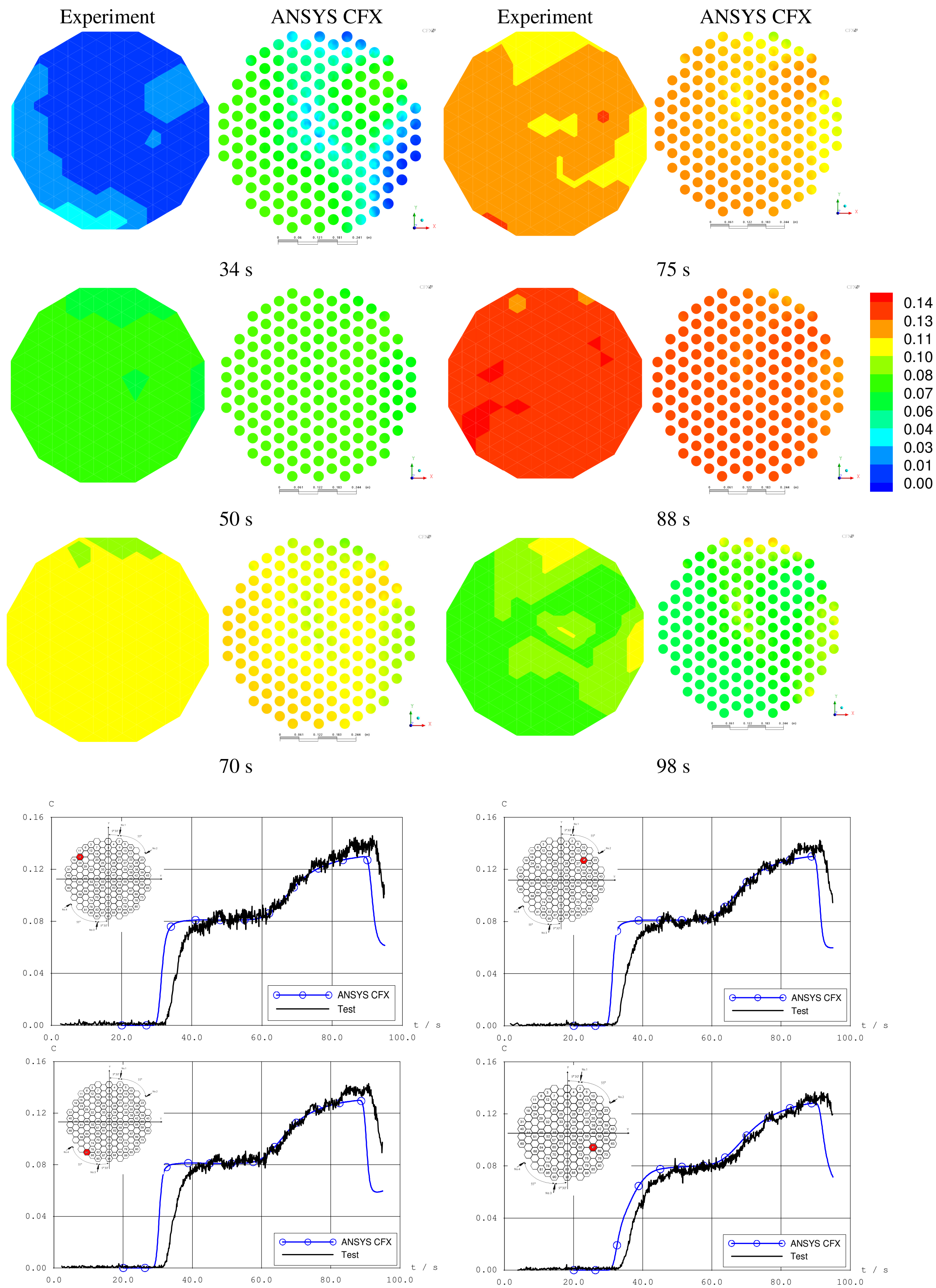

Fig. 7: Change of concentration at the core inlet

According to the calculational data, coolant with the salt solution goes downwards out of Loop №2 inlet nozzle in the downcomer to the opposite side. Salt concentration in the core inlet first appears at the opposite side of the model relative to the inlet nozzle of Loop №2. Then it increases in the core centre and further directly under the inlet nozzle itself leaving the intact areas to the left and to the right of the latter. Then by 50 second of the process salt concentration levels in the entire cross-section at the core inlet.

At 60 second the front of salt concentration reaches the core inlet for another time and the above scenario of its increase in the cross-section is repeated. The second cycle is over at about 90 second of the process . Then salt concentration decreases because of termination of injection that took place somewhat earlier, but due to the transportation delay it takes place later.

5. CONCLUSION

CFD calculations of the salt concentration distribution at the entrance to the core model of the 4-loop test facility modeling reactor VVER-1000 was fulfilled with the complex ANSYS CFX for the experiments with asymmetric saline injection into loops. Results of CFD analyses demonstrated very good agreement with the experimental data.

General conclusion with regard to mismatch of experiments and calculations could be the following. Calculations depict another value of flow displacement in downcomer and the area of interaction of mixing streams from adjacent loops. The reason of this mismatch may be the simplified representation of loops without the exact pump model that yields disregarding of realistic velocity profile in loops and namely the vortex of coolant downstream pump impeller up to loop nozzles.

CFD analyses allows for taking into account in-detailed characteristics of operating centrifugal pumps as well as propagation of corresponding flow disturbances along the loops with valves and other equipment. This will enable to define realistic velocity profile at the location of loop nozzles and upper part of downcomer thus reducing mismatch of analyses. This analytical and experiments with specific instrumentation will be performed next future.