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Studies of turbulent coolant mixing flows in the new generation reactors

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Abstract. Due to studying of the flow parameters in the downcomer the bottom plenum of the nuclear reactor can be carried out with the help of CFD programs, the work is devoted to experimental researches in the field of pressurized water reactor with the purpose of creation of benchmarks for verification of domestic codes of computational hydrodynamics. Such data must have high spatial resolution, high resolution and high accuracy of the measurements. It makes necessary to apply complex experimental methodologies, measurement instrumentation and careful adjustment of experimental methodology. So a brief description of the experimental stand and its research methodology is given. A spatial conductometric measuring system that allows to study the processes of turbulent mixing of flows in the complex geometry of the nuclear reactor is presented. The description of experimental research and their results are presented. Conclusions are drawn about the prospects of using spatial conductometry as a vortex-resolving measurement method.

1 Introduction

Processes of mixing of coolant flows with different physical properties take place during the operation of nuclear reactor. Local deviations of the parameters from the normal ones can lead to reactive, thermal engineering violations of normal operation. Processes that occur when the coolant parameters deviate from the permissible values need to be described using CFD codes, which must undergo a verification procedure on the basis of representative experimental data.

Software products for CFD actively developing now in Russia and abroad, allowing to describe these processes that need verification. In view of the high cost and complexity of carrying out field experiments, most of the phenomena occurring in the equipment of nuclear reactor can be studied on models operating on water at pressures close to atmospheric [1].

Applied studies of mixing processes, suitable for verification, determine the use of modern and reliable detection methods in experiments [2-5]. These include the conductometric method using a spatial sensor. In foreign studies, measuring systems with conductometric sensors are widely used in the study of mass transfer processes [6, 7], due to the high accuracy, clarity and informativeness of the results obtained. However, foreign

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research did not cover a number of issues, among which: Reynolds numbers are far from the values typical for pressurized water reactors, the problem of scaling CFD calculations results, the criteria for determining the minimum required grid size have not been developed, the order of influence of individual physical characteristics on mixing processes has not been established . Previous studies indicate the relevance of using the matrix conductometric measurement method in the study of heat and mass transfer [8, 9]. Thus, it is necessary to carry out a more detailed study of hydrodynamic processes under complex nuclear reactor's geometry [10-15].

2 Experimental facility

2.1 Opportunities of experimental facility

Currently, for experimental research and verification of software for CFD at the Department of Atomic and Thermal Stations at the Nizhniy Novgorod State Technical University n.a. R.E. Alekseev put into operation a multi-purpose large-scale experimental facility [16].

The simplified scheme of this facility is shown in Figure 1. It is a two-circuit installation. The equipment of this facility makes it possible to create regimes of both laminar and turbulent flows at different temperatures, flow rates and impurity concentrations in the coolant flow.

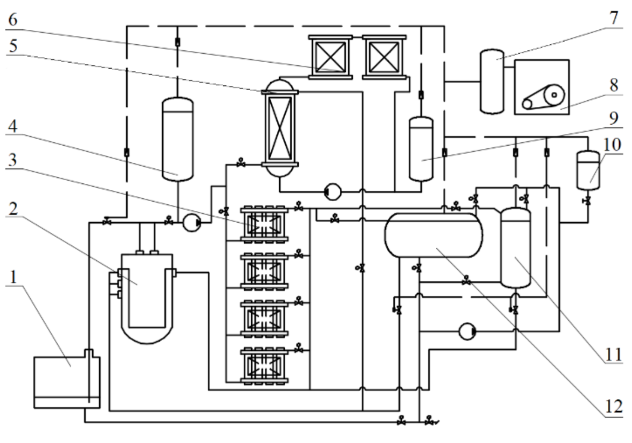

Fig. 1. Simplified scheme of experimental facility. 1 – drainage tank (15 m^3), 2 – test model of reactor, 3 – electrical heating units, 4 – pressurizer of the primary circuit, 5 – heat exchanger of primary and secondary circuits, 6 – air cooled heat exchangers, 7 – air receiver, 8 – compressor unit, 9 - pressurizer of the secondary circuit, 11 – hydraulic accumulator 1(3 m^3), 12 – hydraulic accumulator 2(10 m^3).

The parameters under which simulation can be performed are shown in Table 1.

Table 1. The main characteristic of experimental facility.

Parameter	Value
Number of simulating loops coolant	up to 6
Power of heating units (total), kW	800
Cooling circuit power (maximum), kW	960
The flow through an experimental model, m^3/h	up to 200
Mixing flow temperature, °C	15-200
Pressure in the flow mixing circuit, kgf/cm^2	Up to 20

The general layout of the stand assumes the organization of three types of experimental regimes:

- isothermal mixing in an open loop (for studies using flows with different impurity concentrations);
- non-isothermal mixing in a closed (for studies using different temperature flows);
- non-isothermal mixing in an open circulating loop (for studies using multi-temperature flows).

2.2 Description of experimental mode

In the most "complicated" mode (non-isothermal mixing in a closed loop), the coolant transfers in the following way: under the action of a circulation pump of the mixing circuit coolant is delivered to the collector of the electric heating unit, after which it is divided into two parts. One part is sent to the distributing collector of the electric heating installation, where it is distributed between four parallel connected electric heating units, where coolant is heated, and removing heat from the heating elements. At the exit from this installation, the "hot" coolant flows are sent to the drain collector, where they are combined. Then the flow enters the pipeline, after that it is sent to the "hot collector" of the coolant supply system to the test model. The other part of the coolant under the action of the pump head is directed through the pipeline to the coil heat exchanger of the cooling system, where it transfers heat to the coolant of the second circuit. The "cool" coolant enters the pipeline, and then into the "cool collector" of the coolant supply system to the model. After mixing the flows in the test model, the coolant is transferred to the "drain collector" of the system, from where it is fed through the pipeline again to the pump unit. The closed loop system is equipped with all necessary auxiliary systems, including systems for volume compensation, air removal, drainage, etc.

3 Measuring system

The measuring system of the stand consists of the technological part necessary for monitoring the operating parameters of the experimental facility and the research part, which necessary for determination of physical characteristics in the field of turbulent mixing flows. This measuring system was developed together with S.S. Kutateladze Institute of Thermophysics, Siberian Division of the Russian Academy of Sciences. The parameters of the measuring system of the stand are presented in Table 2 and 3 [17].

Table 2. The main parameters of technological part of measuring system.

Parameter	Value
Number of temperature sensors	29
Number of pressure sensors	23
Number of flow sensors	14
Number of level meters	5
Number of salt control sensors	12
Number of controllable valve elements	70

Table 3. The main parameters of research part of measuring system

Parameter	Value
Number of sensors monitoring the salt content of flow:	
- in the reactor lowering chamber	54 (3 planes of 18 sensors)
- at the inlet and outlet of the reactor core	2 (5x5 strings)

Frequency of independent interrogation of sensors, Hz	100
Range of conductivity of the working medium, μS / cm	10-4000

The research part is represented by conductometric sensors of the mesh and rod structure. The water mesh sensor is installed at the input and output of the area simulating the channels of the core (measuring areas along the centers of the channel-simulators). Water mesh secsor is a set of strings located in two crossed planes rotated relative to each other by 60̊. Thus, any two strings of adjacent layers are cross-sections. The area located between strings of the sensor in a place from the visible intersection forms a conductometric cell. The set of conductometric cells between the electrodes forms the measuring region of the mesh sensor. Rod sensors are installed throughout the reactor's lowering chamber (in three planes with an azimuth of 20° between neighboring sensors). Each sensor has three pairs of electrodes, between which a conductometric cell is formed. The characteristics of the measuring system make it possible to work with flows in a wide range of conductivities of working media, as well as to obtain frequency-energy characteristics of fluctuations in the values of the local concentration for the subsequent reconstruction of the spectrum of turbulent pulsations in the flow. Figure 2 and 3 shows sensors, figure 4 show their placement in the experimental model [18].

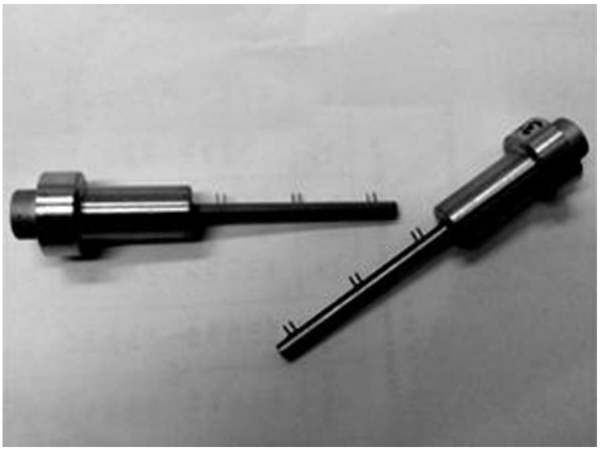

Fig. 2. Sensors or the rod structure.

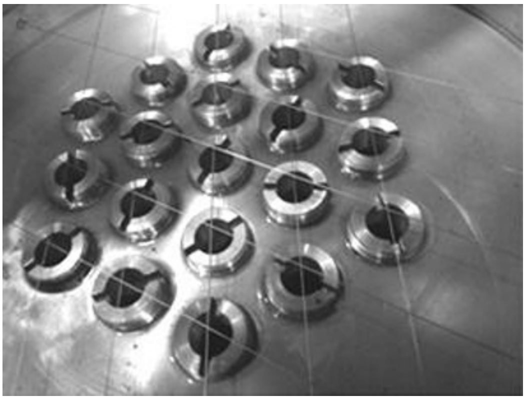

Fig. 3. Sensors or the mesh structure.

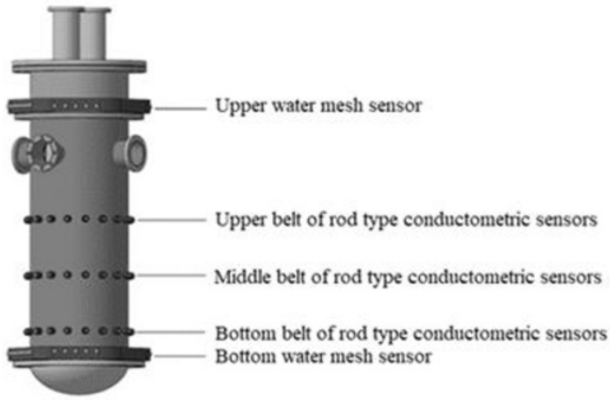

Fig. 4. Placement of the sensors in the experimental model.

4 Experimental research

Calibration of the measuring system was carried out, as a result of which the dependence of the voltage on the conductivity of the medium was established for each conductometric cell. In general, this dependence is affected by: the degree of tension of the sensor strings, directly the conductometric cell value, contamination of the conductors.

After the establishment of these dependencies, a series of experiments was carried out. To study the independent influence of the parameters included into the key criterion (Re number) the experimental mode matrix was developed (Table 4). Re number is varied from 10^4 up to $4 \cdot 10^4$ by independent change:

- of flow speed (by the flow rate variation from 7 to 57 m^3/h),
- of medium viscosity (by the temperature variation from 20 to 80 ^oC).

Matrix of experimental modes is planned to be expanded for variations of hydraulic diameter of the flow (by usage of test models of a larger size).

The movement of the coolant was organized as follows: the coolant pre-injected into the hydraulic accumulator 1 and 2, under the influence of the high-pressure air system, enters the valve block where coolant expelled from the hydraulic accumulator 2 is further divided into 3 equal flows. As a result, 4 flows (3 "fresh" and 1 "salted") enter the test model (the flow diagram of the coolant transfer within the test model is shown in Figure 5). During the movement of coolant through the descending chamber, it passes through 3 rows of rod sensors. These sensors make possible to fix the twist of the coolant. After the descent chamber, the coolant enters the lower mixing chamber, where turbulent mixing takes place. Lower mesh sensor is situated in this chamber. This sensor allows to fix the distribution of thermophysical properties of the flow during the mixing process. After the mixing chamber, the flow is separated and passes through 19 channels-simulators of the core of the reactor model. At the outlet of the channels, the upper mesh sensor allows the amount of concentration equalization to be recorded during the passage of the channels of the core by the coolant.

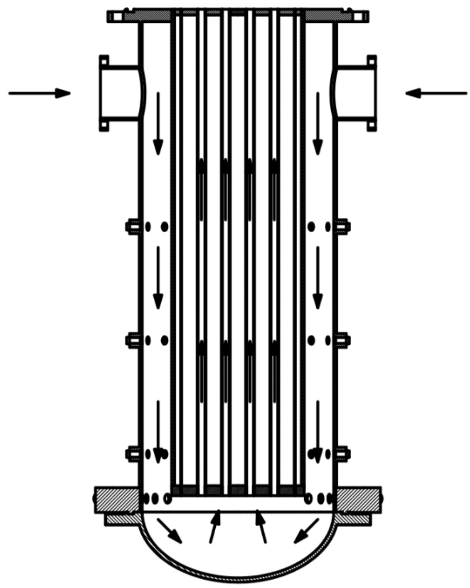

Fig. 5. The flow pattern of the coolant inside the test model

Table 4. The main parameters of research part of measuring system

Parameter	Experimental mode name[a]		
	10/20	20/20	20/56
Flow rate in TMb, m3/h	18.9 (19.0)	37.8 (37.7)	18.9 (19.1)
Flow temperature, °C [b]	20 (22)	20 (20)	56 (61)
Pressure in HA1,2, kg/cm2 [c]	2.5 (2.3)	2.5 (2.2)	2.5 (2.1)
Approximate concentration in HA2 (HA1), mg/l	444 (798)	599 (1286)	433 (752)

[a] for all modes the value before slash – Re value in downcomer in thousands, value after slash – temperature of the flow, °C

[b] nominal and actual (in brackets) values

[c] for all modes the value of pressure is excessive

After processing the experimental data, flow mixing patterns were constructed, the distribution of the introduced tracer along the descending chamber was determined, also values were obtained: average values of the concentration in the measuring cells of the sensors, the maximum and minimum values among them [19, 20], the difference between the maximum and minimum values (this values characterize the integral unevenness of the field. It should be noted that in absolutely all experimental modes a twist of the coolant flow was discovered. It was indicated by the readings of the rod sensors, as well as the detection of the "spot" of the contrasting coolant in the area of the opposite tracer input on the bottom water mesh sensor. For example, in Figure 6 presents mixing patterns by lower water mesh sensor for the 20/20 experimental mode and Figure 7 shows mixing pattern by upper water mesh sensor for same experimental mode. As a result of this experimental mode was established:

- the maximum averaged concentration is 37%;
- the minimum value of the average concentration is 8%;
- integral unevenness - 28%;
- the maximum instantaneous concentration value is 52%.

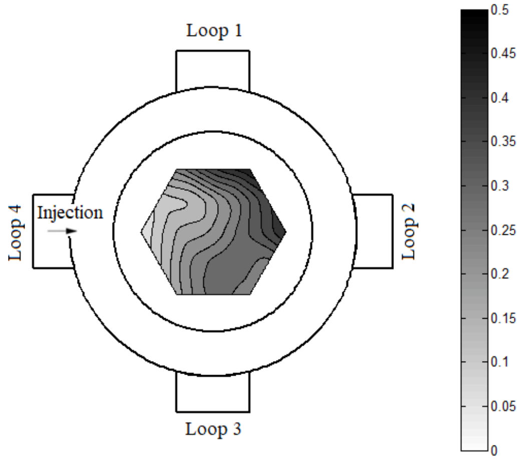

Fig. 6. Flow mixing pattern by bottom water mesh sensor

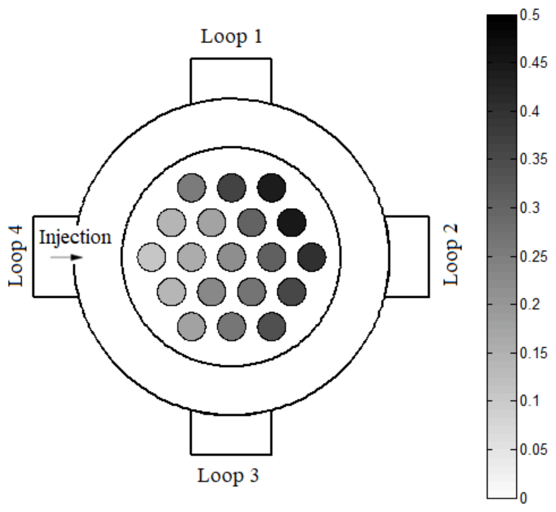

Fig. 7. Flow mixing pattern by upper water mesh sensor

5 Conclusion

Experimental studies of processes of turbulent mixing in a model of pressurized water reactor conducted in the Reynolds number range $(10\text{-}30)\cdot10^3$ revealed the patterns of flow with different experimental parameters. Each experimental mode showed that in the downcomer the flow is twisted to an angle about 180○. Thus, the tracer spot is observed in the region of the opposite input region in any experimental mode.

As a result of this experiment, we can conclude, that the use of spatial conductometry as a method for studying and visualizing turbulent vortices is a reliable and very accurate tool for verifying eddy-resolving models of CFD programs. The obtained data are used as a base for experimental data for verification of Russian 3D CFD programs, and more of that for adaptation to the calculation of turbulent mixing of nonisothermal flows in pressure chambers of promising nuclear power units.

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References

1. A.V. Budnikov, D.N. Sveshnikov, R.I. Romanov, Proc. of conf. Problems od CFD-codes verification and application in atomic energy, 17-18 (2016)
2. H.F. Velasco, O.M. Pena, H. Rodrigiues, Flow measurment and instrumetation **45,** 255-273 (2015)
3. M.J. Da Silva, *Impedance Sensors for Fast Multiphase Flow Measurement and Imaging*, Ph.D. dissertation (Dresden, Technische Universitat Dresden Publ, 2008)
4. D.A. Sergeev,A.A. Kandaurov, Y.I. Troitskaya, *A particle-image velocimetry system for measurement of velocity flow fields for investigations of thermohydraulic processes on the large-scale benchmark of a promising fast-neutron reactor,* Instruments and Experimental Techniques, **60** (2017)
5. D.A. Sergeev, A.A. Kandaurov, Y.I. Troitskaya, *The particular use of PIV methods for the modelling of heat and hydrophysical processes in the nuclear power plants,* J.Phys.: Conf. Ser. **891** (2017)
6. A. Ylonen, W.M. Bissels, H.M. Prasser, Nuclear Engeering and Design, **7, 241,** 2484-2493 (2011)
7. O.M. Vokhnik, A.M. Zotov, P. V. Korolenko, Yu. V. Ryzhikova, *Modeling and processing of stochastic signals and structures* (Moscow, University Book, 2013)
8. S.M. Dmitriev, D.L. Zverev, O.A. Byh, Y.K., N.M. Sorokin, V.A. Farafonov, *Main equipment of nuclear power plants with thermal reactors* (Moscow, Mashinostroenie, 2013)
9. M.A. Bolshuhin, A.V. Budnikov, V.I. Fomichev, D.N. Sveshnikov, R.I. Romanov, Proceedings of the Nizhny Novgorod State Technical University n.a. R.E. Alekseev, **2, 99,** 117-125 (2013)
10. U. Rohde, S. Kliem, T. Hohne, R. Karlsson, B. Hemstorm, J. Lillington, T. Topipila, J. Elter, Y. Bezrukov, Nuclear Engineering and Design, **235,** 421-443 (2005)
11. I. Farkas, E. Hutly, T. Farkas, A. Takaxas, A. Guba, I Toth, Nuclear engineering and technology, **48(4)**, 941-951 (2016)
12. K. Kim, D.J. Euh, T.S. Kwon, E. Schleicher, Proc. of Specialists Workshop on Advanced instrumentation and Measurment Techniques for Nuclear Reactor Thermal Hydraulics (SWINTH-2016), **16,** 1-14 (2016)
13. K. Kim, D.J. Euh, I.C. Chu, Y.J. Youn, Nuclear Engineering and Design, **265**, 957–966 (2013)
14. N. Forgione, V. Baudanza, I. Angelo, D. Martelli, *Downcomer and lower plenum experimental facility*, Report RdS, ENEA (2011)

15. V. Volkov, L. Golibrodo, A. Krutikov, U. Nadinsky, A. Skibin, Verification of CFD reactor model on the fast borated water injection system test results, Proc. of the 10th international conf. «NPP VVER saftey assurance» (2017)
16. S.M. Dmitriev, A.E. Khrobostov, A.A. Barinov, S.B. Ivanov, A.S. Veselkov, Experience in designing a large-scale verification bench for studying the mixing of non-isothermal flows in the body of a water-cooled reactor, 21st Nizhegorodskaya sessiya molodyh uchenyh (2016)
17. A.A. Barinov, A.V. Varentsov, V.G. Glavnyj, S.M. Dmitriev, M.A. Legchanov, A.V. Ryazanov, A.E. Khrobostov, *Implementation of the method of spatial conductometry for experimental research of the processes of mixing intra-reactor flows in modern nuclear units*, Proceedings of the Nizhny Novgorod State Technical University n.a. R.E. Alekseev, **2** (2017)
18. A.A. Barinov, S.M. Dmitriev, A.E. Khrobostov, V.G. Glavnyj, Devices and methods of measurements, **7(3)**, 247-255 (2016)
19. G. Taylor, Proceedings of the Royal Society of London **223, 1155**, 446-468 (1954)
20. M.A. Polunin, Scientifical transport problems of Siberia and Far East, **1**, 170-171 (2009)