Description of the experimental studies of coolant mixing flows in the reactor pressure vessel

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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 studying 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 about the prospects of using spatial conductometry as a vortex-resolving measurement method are drawn.

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 the CFD codes, which must undergo a verification procedure on the basis of representative experimental data.

Software products for CFD are actively developing now in Russia and abroad, allowing one to describe these processes that need verification. In view of the high cost and complexity of carrying out the 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 the atmospheric.

Applied studies of mixing processes, suitable for verification, determine the use of modern and reliable detection methods in experiments. 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 due to the high accuracy, clarity and informativeness of the results obtained. However, foreign research did not cover a number of issues, among which are the following: Reynolds numbers are far from the values typical of pressurized water reactors, problem of scaling CFD calculations results, 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.

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Previous studies indicate the relevance of using the matrix conductometric measurement method in the study of heat and mass transfer [1, 2]. Thus, it is necessary to carry out a more detailed study of hydrodynamic processes under complex nuclear reactor’s geometry.

2. Experimental facility
Currently, a multi-purpose large-scale experimental facility is put into operation at the Department of Atomic and Thermal Stations at the Nizhniy Novgorod State Technical University n.a. R.E. Alekseev for experimental research and verification of software for CFD[3].

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 the regimes of both laminar and turbulent flows at different temperatures, flow rates and impurity concentrations in the coolant flow.

Figure 1. Simplified scheme of experimental facility. 1 – drainage tank (15 m³), 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 m³), 12 – hydraulic accumulator 2(10 m³),

The parameters required for simulation are shown in Table 1.

Table 1. The main characteristic of experimental facility

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| Number of simulating loops of coolant circulation | 6              |
| Power of heating units (total), kW             | 800            |
| Cooling circuit power (maximum), kW            | 960            |
| The flow through an experimental model, m³/h    | up to 200      |
| Mixing flow temperature, °C                    | 15-200         |
| Pressure in the flow mixing circuit, kgf/cm²   | up to 20       |
The general layout of the stand assumes 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 loop (for studies using different temperature flows);
- non-isothermal mixing in an open circulating loop (for studies using multi-temperature flows).

In the most "complicated" mode (non-isothermal mixing in a closed loop), the coolant is transferred in the following way: under the action of a circulation pump of the mixing circuit the coolant is delivered to the collector of the electric heating unit, then 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 removed 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 of the test model. The other part of the coolant is directed under the action of the pump head 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 the "cool collector" of the system of coolant supply 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 is 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 Branch of the Russian Academy of Sciences. The parameters of the measuring system of the stand are presented in Tables 2 and 3 [4, 5].

| 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: | 54 |
| - in the reactor lowering chamber (3 planes of 18 sensors) | |
| - at the inlet and outlet of the reactor core | 2 |
| 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 sensor is a set of strings located in two crossed planes rotated relative to each other by 60°. Thus, any two strings of adjacent
layers are the cross-sections. The conductometric cell is the area located between two strings of the mesh sensor, in the place of their visible crossing. 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 the 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 shows the sensors, as well as their placement in the experimental model [6].

![Research part of measuring system](image)

**Figure 2.** Research part of measuring system

4. Experimental research

The measuring system was calibrated, as a result, the dependence of voltage on medium conductivity 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 $10^3$ up to $4 \times 10^4$ by independent change in:

- flow speed (by the flow rate variation from 7 to 57 m³/h),
- medium viscosity (by the temperature variation from 20 to 80°C).

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 is pre-injected into the hydraulic accumulator 1 and 2, under the influence of the high-pressure air system, it enters the valve block, where it is expelled from the hydraulic accumulator 2, further it is 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 3). During the movement of coolant through the descending chamber, it passes through 3 rows of rod sensors. These sensors make it 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 one 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.

![Figure 3. The flow pattern of the coolant inside the test model](image)

**Table 4.** Experimental modes

| Parameter                              | Experimental mode name\(^a\) |
|----------------------------------------|------------------------------|
|                                       | 10/20                        |
| Flow rate in TM\(^b\), m\(^3\)/h       | 18.9                         |
|                                        | (19.0)                       |
| Flow temperature, °C                   | 20                           |
|                                        | (20)                         |
| Pressure in HA1,2, kg/cm\(^2\)         | 2.5                          |
|                                        | (2.3)                        |
| Approximate concentration in HA2 (HA1), mg/l | 444                          |
|                                        | (798)                        |
|                                        | 20/20                        |
| Flow rate in TM\(^b\), m\(^3\)/h       | 37.8                         |
|                                        | (37.7)                       |
| Flow temperature, °C                   | 20                           |
|                                        | (20)                         |
| Pressure in HA1,2, kg/cm\(^2\)         | 2.5                          |
|                                        | (2.2)                        |
| Approximate concentration in HA2 (HA1), mg/l | 599                          |
|                                        | (1286)                       |
|                                        | 20/56                        |
| Flow rate in TM\(^b\), m\(^3\)/h       | 18.9                         |
|                                        | (19.1)                       |
| Flow temperature, °C                   | 20                           |
|                                        | (20)                         |
| Pressure in HA1,2, kg/cm\(^2\)         | 2.5                          |
|                                        | (2.1)                        |
| Approximate concentration in HA2 (HA1), mg/l | 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, the flow mixing patterns were constructed, distribution of the introduced tracer along the descending chamber was determined, also the following values were obtained: average values of concentration in the measuring cells of the sensors, maximum and minimum values among them, 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 4 for the 20/20 experimental mode, mixing patterns by water mesh sensors are presented. As a result of this experimental mode, the following was established:

- the maximum averaged concentration is 37%;
- the minimum value of the average concentration is 8%;
- integral unevenness is 28%;
- the maximum instantaneous concentration value is 52%.
5. Conclusion
Experimental studies of processes of turbulent mixing in a model of pressurized water reactor conducted in the Reynolds number range \((10-30) \times 10^3\) revealed the patterns of flow with different experimental parameters. Each experimental mode showed that in the downcomer the flow is twisted by an angle about \(180^\circ\). 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 the pressure chambers of promising nuclear power units.

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