Experimental investigations of velocity and temperature fields, stratification phenomena in a integral water model of fast reactor in the steady state forced circulation

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Abstract. The results of experimental investigations of velocity and temperature fields on integrated water model of a fast reactor for the forced circulation mode are presented. The significant gradients and temperature pulsations are fixed on boundary lines of stratified and recirculation formations not only in the peripheral area of the top chamber of the reactor above the side screens, but in the cold and the pressure chambers, elevating the enclosure, the cooling system of the reactor, at the outlet of the intermediate heat exchangers. The data obtained are intended for verification of the codes for a substantiation of thermohydraulic and strength characteristics of the reactor equipment.

Key Words: fast reactor, stratification, temperature field, temperature pulsations.

1. Introduction

Circuit of the coolant in reactor on fast neutrons (FR) is a complex combination of series consistent and parallel connected elements with different orientation in the gravitational field, the geometrical characteristics of flow areas which sharp changed the direction of travel. The coolant in the FR always not isothermal due to irregularities of energy, heat removal, the temperature difference between the nodes of circulation circuit. Experience in operating BN-600 reactor and results of special measurements, as well as experimental studies on models showed temperature stratification of coolant in the elements of reactor vessel with a large volume of coolant [1 – 8].

Processes of coolant temperature stratification, which does not provide design documentation, radically change the structure of the coolant flow and temperature conditions, lead to the formation of stagnant and recycling formations, restructuring character of the flow and temperature conditions.

The experimental results show [9] there are internal waves in stratified interfaces isothermal zones that cause temperature fluctuations on the walls of the reactor equipment. This leads to the effects on structural materials, thermal fatigue and reduce resource-core hardware, which is confirmed by the results of work [10].

Stratification of the coolant also has a significant effect on the nuclear-physical characteristics of the reactor, the physic-chemical interaction between the coolant and construction materials, the processes of deposition of oxides in the cold stagnant zones of the reactor tank, requires justification for installing full-control sensors, placement of cold filter traps oxides in the tank. Today the calculated codes allow you to receive only the picture as averaging the temperature distribution in the flow of coolant, the fluctuating temperature characteristics are generally not predicted by calculations [11].

Thermal hydraulics modeling errors in fast reactors in the fragmented sector models with isothermal flow associated with the neglect of the spatial 3-D effects and thermal flow heterogeneity.

The goal of this work is to obtain the results of the investigations of spatial temperature distribution in the circuit and the velocity in the upper plenum at steady-state conditions of forced circulation, providing verification of the calculated thermal-hydraulic codes, as well as investigations of gradients and fluctuations of temperature in the stratified interfaces between the main flow and recirculation, stagnant formations, required to develop techniques and codes for calculating of the thermal stress and fatigue of materials for reactor vessel and equipment.

2. Experimental equipment and questions of modeling

The primary circuit of new generation FR which described in [12] is modeled on the facility "V-200" JSC "SSC RF – IPPE" of integrated water model on the scale of ~ 1:10 (*FIG.* 1, 2). The first circuit of the reactor model consists of two parallel loops each of them contains two models of intermediate heat exchanger (IHE), simulator of primary coolant pump (PCP) and one autonomous heat exchanger (AHE). The parameters of the second and the intermediate circuit model (flow rate and temperature) was taken out of the calculation justification processes forced circulation and emergency cooling. In the third circuit water used with an adjustable flow rate. Maximum energy generation of the simulator core of model is ~ 100 kW (*FIG.* 2). A detailed description of the experimental model and experimental conditions are presented in [13].

Questions of modeling thermal hydraulics for fast reactors on integrated water model discussed in detail in [14, 15]. To avoid difficulties of strict criterion modeling heat transfer processes in the reactor core and the heat exchangers are modeled by uniform volumetric heat generation (heat absorption) preserving the coefficients of hydraulic resistance for reactor and model. These deviations can be evaluated by calculation of the relevant codes.

In the regimes of forced circulation the accurate simulations was carried out by the Froude number and Peclet number.

Coolant temperature stratification characterized by the occurrence of stagnant, recirculating formations with large temperature gradients on stratified interfaces. The criteria for determining the similarity of flows in a stably stratified areas of the coolant are the Froude number (Fr), the Peclet (Pe) and the local gradient Richardson number $\mathrm{Ri} = g\beta(\partial t/\partial z)/(\partial w/\partial z)^2$. The characteristics of a stably stratified flow of coolant are frequency of Vaysyalya – Brent $N^2 = (g/\rho)(\partial\rho/\partial z)$ and buoyancy scale $l_b = \rho(\partial\rho/\partial z)^{-1}$. In stably stratified turbulent flow the maximum size of the vortices can not exceed the scope of buoyancy. Therefore, large-scale vortices larger than the scale of buoyancy suppressed and flow along the stratified region section in the form of internal waves. Internal waves create temperature fluctuations in the wall material of equipment with frequency $f \leq N$.

The viscous fluid simulation on the Froude number and Richardson number is impossible while maintaining the Reynolds number (Re). Investigations at numbers $\mathrm{Re} > 10^4$ showed that the size of stagnation and recirculation formations (with $\mathrm{Fr}_m = \mathrm{Fr}_r$) are not changed, so the accurate modeling on Re number is not required.

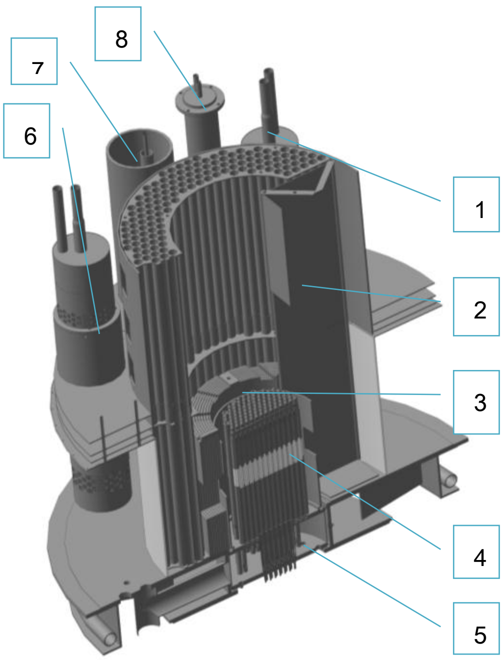

FIG. 1. The main elements of the primary circuit water facility "V-200": 1, 6 – intermediate heat exchangers (IHE); 2 – elevating enclosure; 3 – elements innertank protection; 4 – core (FSA simulators); 5 – the pressure chamber; 7 – simulator of primary coolant pump (PCP); 8 – autonomous heat exchanger (AHE)

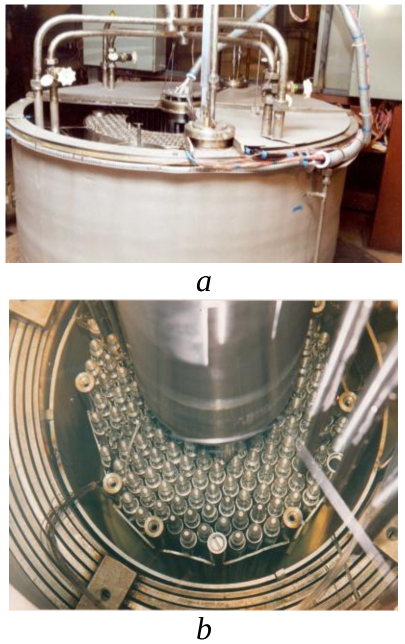

FIG. 2. General view of the integrated model FR on facility "V-200" (a) and top view of the core fuel subassembly simulators (b)

3. The system of measurements, data collection, processing and management

Automated system for collecting, processing and management of thermal-hydraulic parameters of the model contains more than 400 sensors. Taking into account the specificity of the experiments, it is divided into subsystems: the slow measurements (survey of all sensors for 1 s); fast measurement (includes 120 channels with a sampling frequency of 10 Hz); correlation measurements of local velocities; control of flow rate, temperature, power heaters. Error of measurement does not exceed ± 0.5°C of temperature ± 0,1 kPa of pressure, voltage ± 1 V, current ± 1 A.

Cartogram of subassemblies core simulators of integrated water model of fast reactor is shown in *FIG.* 3 a. Numerals indicates a number of simulators fuel subassemblies (FSA) which thermocouples were installed. Three similar mobile temperature thermal probe (TP) and correlation probe velocity for the investigation at the same time of spatial distributions of temperature and velocity in the upper chamber are further used (*FIG.* 3 b).

Measurements of the velocity field on the integral fast reactor model in the upper chamber were carried out using a multi-components thermocouple sensor [16], developed by a team of specialists of MPEI – JIHT RAS [17]. The measurements were performed by the correlation method at steady nominal mode and emergency cooling. *FIG.* 2 shows one of four projections thermocouple (copper-constantan) velocity sensor. The diameter of the thermocouple junction was 0.2 mm. The velocity fields are measured by the correlation method using the natural background of turbulent fluctuations of temperature borne stream [18]. Selection of the velocity field measurement method was due to the relative miniaturization of the velocity sensor, its high operating properties and the absence of the danger of contamination of the hydraulic fluid.

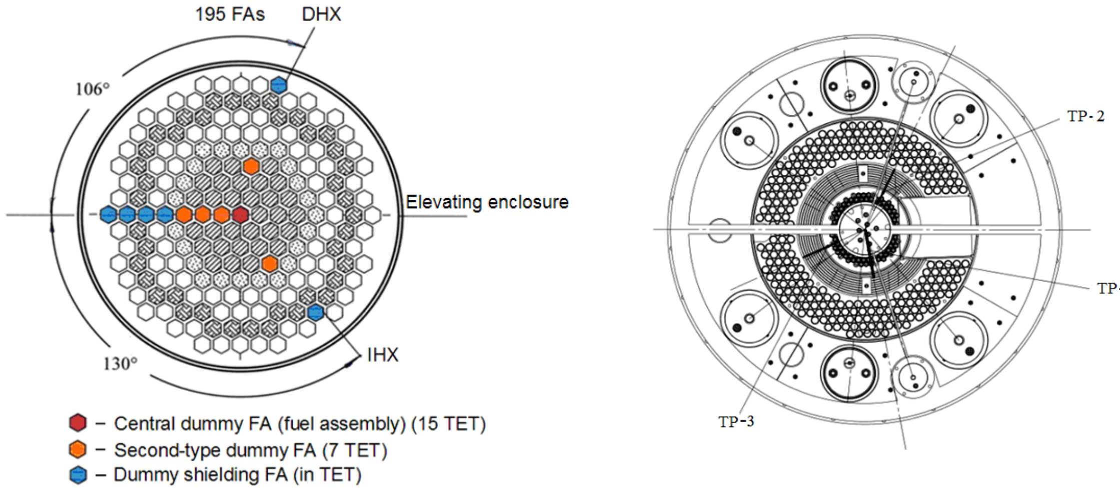

Fig. 3. Cartogram of subassemblies core simulators (a); arrangement of mobile temperature thermal probe (TP) (b)

4. Experimental results

Steady state forced circulation in the fast reactor model simulates the temperature distribution in the reactor tank before going to the regime of decay heat removal. Typical indications of thermocouples of mobile temperature thermal probe (TP-1) installed radially through the 13 mm at a height of 15 mm from the heads of simulators FSA in a stationary nominal forced circulation regime are shown in *FIG.* 4.

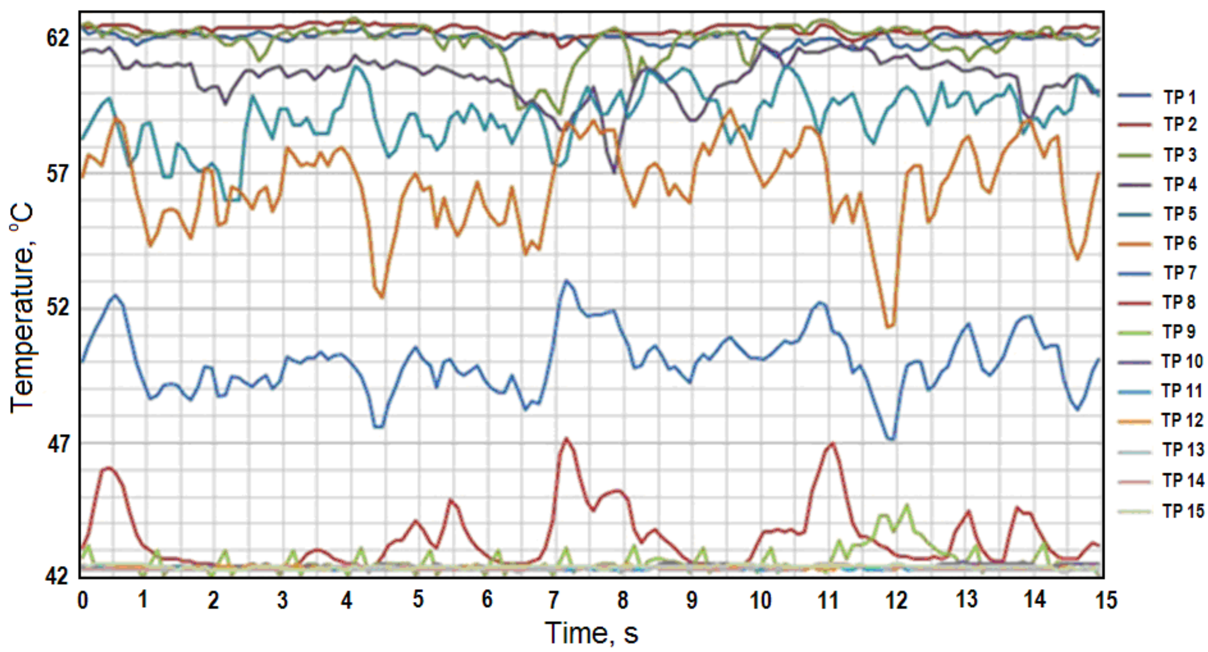

FIG. 4. Indications of thermocouples of thermal probe TP-1 set the radius of core in 13 mm, at a height of 15 mm from the head of FSa simulators in the nominal regime

FIG. 5, 6 are respectively the averaged of temperature field and the fluctuation intensity in the upper chamber obtained by moving the NP probes TP-1 and TP-2 in the steady nominal regime.

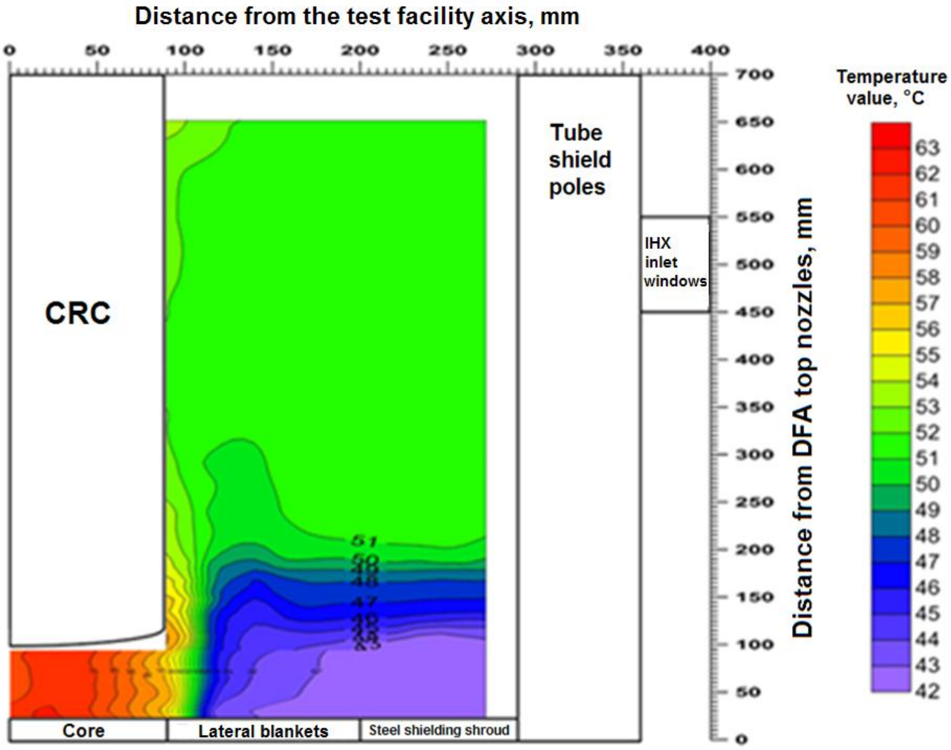

FIG. 5. The field of averaged temperature at the height of the upper chambers obtained by moving of mobile temperature thermal probe (TP-1) and (TP-1) in nominal regime

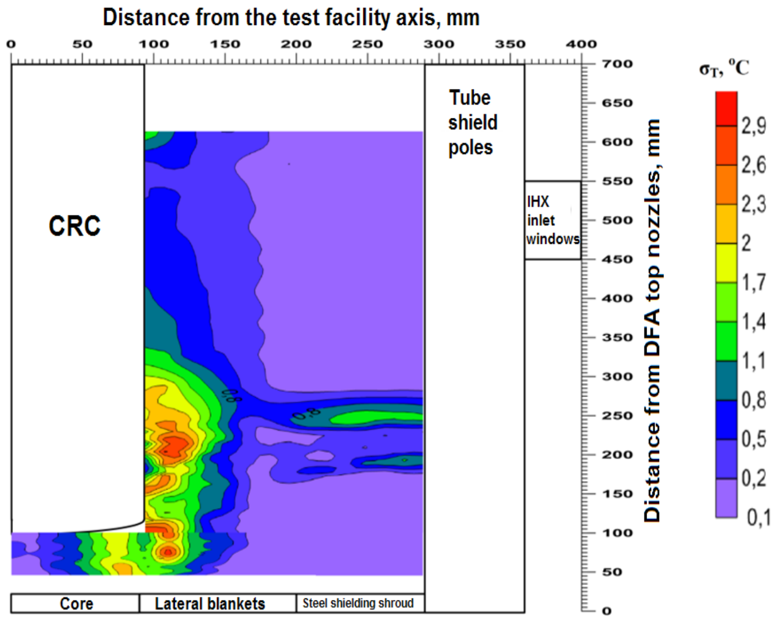

FIG. 6. The intensity of temperature fluctuations on the height of the upper chambers obtained by moving of mobile temperature thermal probe (TP-1) and (TP-1) in nominal regime

Averaged component of velocity field in the vertical, radial and azimuthal directions in the stable regime are shown in *FIG*. 7. It should be noted that the design of the movable probes allow the temperature and the velocity measurements at longer distances than 3 – 4 mm from the rotation central column. In experiments on measuring the velocity component of more than 160 points were obtained for each regime. When checking the results of measurements checked for uniformity of the distribution of correlation on signal spectrum. Spectral signal was divided into parts, the results were compared to determine the correlation of different portions of the spectrum. In the case of instability of the spectrum correlation the result of measurement was withdrawn from consideration.

Note that for different velocity components number of dropped points varies from 35% for the vertical, 75% for the azimuth and 60% for the radial velocity component. This is due to the correlation sensor measurements. The velocity fields recovered from the experimental points by a polynomial triangulation, in *FIG*. 7 also marked the points at which the measurements were taken into consideration for the construction fields.

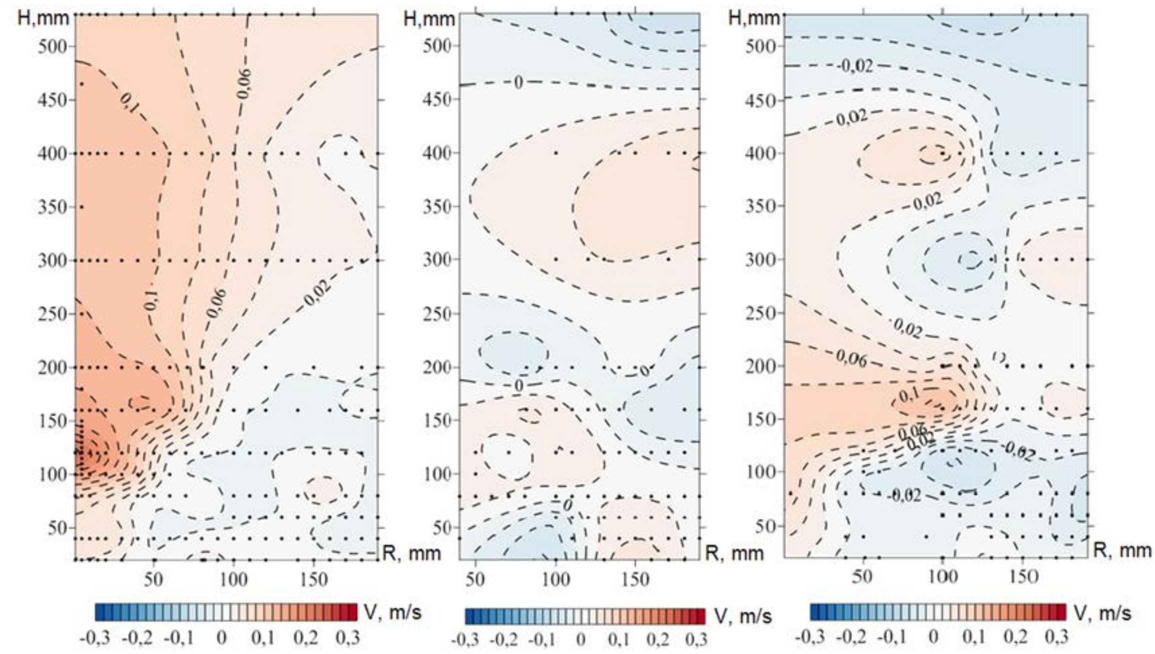

FIG. 7. Fields of averaged velocity components in the upper chamber in nominal regime: the vertical component (a); the radial component (b); the azimuthal component (c)

Averaged temperature field over the side shields in the planes at the same time movement the adjustment of the movable probes TP-2 and PP-3 (shifted in azimuth than 150°) at nominal regime are shown in *FIG*. 8.

The data presented (*FIG*. 5 – 8) follows that the movement structure nonisothermal coolant in the upper chamber of the reactor determined by the action of the lifting force: hot coolant from the reactor core rises upwards along the central section of the column to the interface and form an extensive vortex almost isothermal hot zone in the upper region from which flows into the intermediate heat exchangers. On the periphery of the lower region of the upper chamber of the side shields formed a stable isothermal zone of cold coolant. The size of zone with the growth of flow rate (power installation) increase. Zones of hot and cold coolant radially occupy the entire cross section of the reactor tank.

TP-2 TP-3

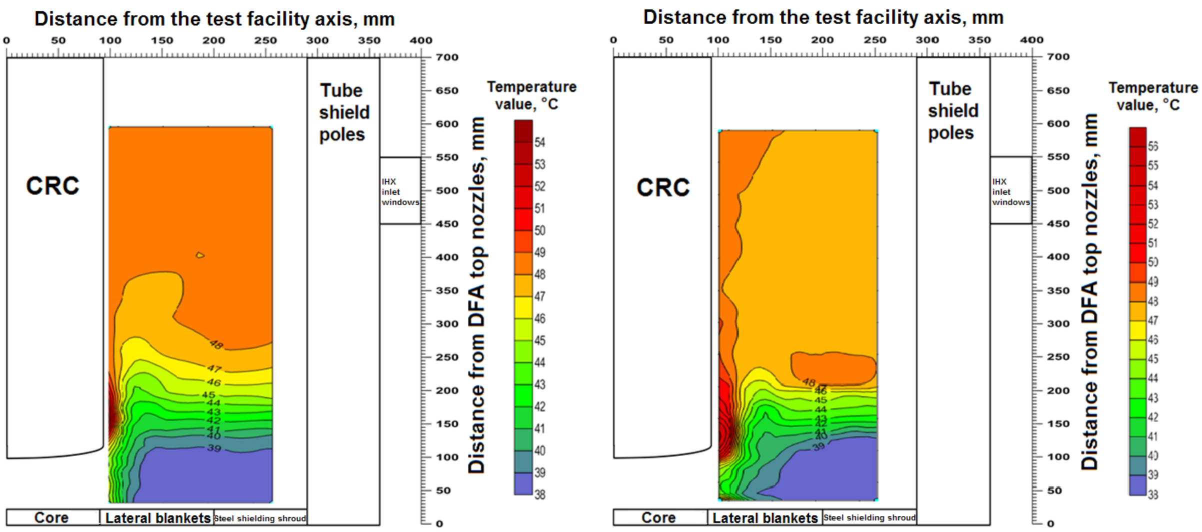

FIG. 8. The averaged temperature field over the side shields in the planes of movement of the movable probes TP-2 and TP-3

The separating layer between the isothermal coolant zones stably stratified with the scale of buoyancy l_b. Turbulent eddies of the top hot and lower cold zones with scales $l > l_b$ suppressed in the separation layer and create internal waves that cause temperature fluctuations in the material of the walls of equipment. Field of vertical component of velocity in the upper chamber in the forced circulation regime consistent with the picture fields of averaged temperature. Distribution of temperature fields and velocity on height of the upper chamber (*FIG.* 7 – 8) is not isotropic in the azimuthal direction. Secondary layered flow in these areas are associated with a radial temperature gradient caused by hot flow along the central rotary column (CRC) and the relatively cold surface of IHE.

For a nominal regime in *FIG.* 9 shows the averaged temperature field on height of some elements intrareactor equipment. The heterogeneity of the coolant temperature at the height of the output window IHE (*FIG.* 9 a) leads to a stable temperature stratification on the height of cold chamber (*FIG.* 9 b). Circulating pumps the first coolant circuit is taken coolant from the upper region of the cold chamber, in the lower region is relatively stable cold coolant stagnation zone in which the possible deposition of oxides. The temperature stratification of coolant on the height of elevator cubicle (*FIG.* 9 c) is characterized by two almost equal isothermal recirculating formations: the hot zone at the top, cold at the bottom and narrow stratified separating layer with temperature drop almost equal to heating in the core.

Staff out the coolant of the fuel subassembly heads (through the side holes) aligns the velocity field at the outlet of core and side screen and does not provide the mixing of non-isothermal flow in the upper chamber.

Investigations on the fragmented sector transparent model of the upper chamber of a fast reactor [15] have shown that the most effective way to intensify the mixing of non-isothermal flow of coolant is the output of the FSA heads in the form of vertical jets. The cold coolant from the side screens is slowing under the influence thermogravitational forces and intensively absorbed between faster rising jets of hot coolant from the core. Mixing process is carried out directly in the coolant flow at the inlet at the bottom of the upper chamber and does not cause temperature fluctuations in the equipment material.

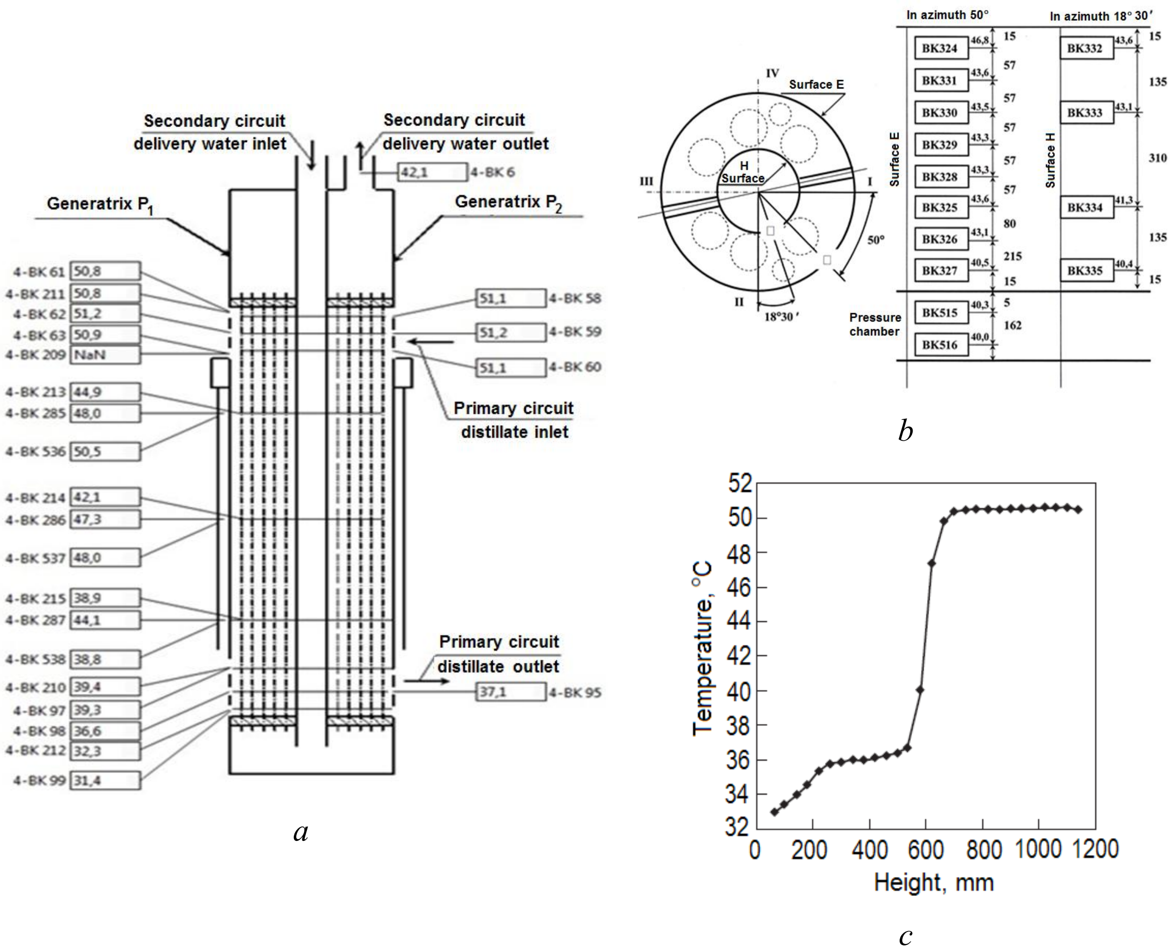

FIG. 9. Distribution of the averaged temperatures on heights: the intermediate heat exchanger (a), the cold and the pressure chamber (b), elevating enclosure (c)

5. Conclusion

The experimental results obtained with the help of specially developed and implemented on a stand system measurements, ensuring high accuracy and high speed of their registration, show that the structure of the movement of non-isothermal coolant in the upper chamber of the reactor model is determined by the action of the lifting force: hot coolant from the core rises along the central section of the column to the interface and forms a nearly isothermal extensive vortex zone in the upper region of the chamber from which flows into the intermediate heat exchangers. Above the side shields formed isothermal cold zone of coolant, the size of which with the growth of total flow rate is increasing. In stratified horizontal interface between the isothermal zones across the cross-section model of the reactor vessel internal waves arise that cause temperature pulsations in the material of the walls of equipment.

A significant and stable temperature stratification coolant is demonstrated not only in the peripheral zone of the upper chamber of the reactor on the side screens, but in the cold and the pressure chamber, elevator cubicle, the cooling system of the reactor vessel, at the outlet of the intermediate heat exchanger. On interfaces stratified and recycling entities recorded large gradients and temperature fluctuations that would reveal the amplitude and frequency characteristics of temperature fluctuations in the potentially hazardous areas.

The findings point to the need to address the phenomena of stratification in justifying the reliability of management, security, design life of fast reactors. The data are intended for verification codes, in particular, the design codes DINROS and GRIF and a new generation of codes HYDRA-IBRAE/LM [19], SOCRAT-BN [20], used to justify the thermal-hydraulic and strength characteristics of the elements of equipment under thermal cycling, as well as directly for the conversion of similarity criteria for the analysis of temperature regimes and thermal cycling characteristics.

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