ISSN 0040-6015, Thermal Engineering, 2017, Vol. 64, No. 7, pp. 496–503. © Pleiades Publishing, Inc., 2017.
Original Russian Text © V.V. Pakholkov, A.A. Kandaurov, A.I. Potseluev, S.A. Rogozhkin, D.A. Sergeev, Yu.I. Troitskaya, S.F. Shepelev, 2017, published in Teploenergetika.

NUCLEAR POWER STATIONS

Experimental Investigation of a New Method for Advanced Fast Reactor Shutdown Cooling

V. V. Pakholkov[a, *], A. A. Kandaurov[b], A. I. Potseluev[a], S. A. Rogozhkin[a], D. A. Sergeev[b], Yu. I. Troitskaya[b], and S. F. Shepelev[a]

[a]*JSC Afrikantov OKB Mechanical Engineering (OKBM), Nizhny Novgorod, 603074 Russia*
[b]*Institute of Applied Physics, Russian Academy of Science, Nizhny Novgorod, 603950 Russia*
**e-mail: pakholkov@okbm.nnov.ru*

Received October 18, 2016; in final form, December 21, 2016

Abstract—We consider a new method for fast reactor shutdown cooling using a decay heat removal system (DHRS) with a check valve. In this method, a coolant from the decay heat exchanger (DHX) immersed into the reactor upper plenum is supplied to the high-pressure plenum and, then, inside the fuel subassemblies (SAs). A check valve installed at the DHX outlet opens by the force of gravity after primary pumps (PP-1) are shut down. Experimental studies of the new and alternative methods of shutdown cooling were performed at the TISEY test facility at OKBM. The velocity fields in the upper plenum of the reactor model were obtained using the optical particle image velocimetry developed at the Institute of Applied Physics (Russian Academy of Sciences). The study considers the process of development of natural circulation in the reactor and the DHRS models and the corresponding evolution of the temperature and velocity fields. A considerable influence of the valve position in the displacer of the primary pump on the natural circulation of water in the reactor through the DHX was discovered (in some modes, circulation reversal through the DHX was obtained). Alternative DHRS designs without a shell at the DHX outlet with open and closed check valve are also studied. For an open check valve, in spite of the absence of a shell, part of the flow is supplied through the DHX pipeline and then inside the SA simulators. When simulating power modes of the reactor operation, temperature stratification of the liquid was observed, which increased in the cooling mode via the DHRS. These data qualitatively agree with the results of tests at BN-600 and BN-800 reactors.

Keywords: advanced fast reactor, emergency heat removal system, natural circulation, check valve, modeling, TISEY test facility, Particle Image Velocimetry

DOI: 10.1134/S0040601517070059

Residual heat removal of advanced sodium-cooled fast reactors is performed via DHRS with DHX immersed in the reactor plenum if cooling by steam generators is impossible. The system of shutdown heat removal consists of four independent loops and each loop includes three heat exchange circuits: the first (reactor), the intermediate, and the air circuits. The first and intermediate circuits use liquid sodium as a coolant, and the air circuit uses atmospheric air. Natural circulation of coolants is implemented in all DHRS circuits.

In the new shutdown cooling method for an advanced fast reactor, the coolant of the decay heat exchanger is supplied to the reactor upper plenum through the check valve and then inside fuel subassemblies. In similar decay heat removal systems of foreign reactors (for example, EFR, PFBR, CEFR [1]), this valve is absent, and the coolant from the decay heat exchanger flows back to the reactor upper plenum [2].

Scaled-down water models of various sizes and complexity are often used in engineering for investigation of thermal hydraulic processes in fast reactors [2, 3]. The use of water instead of sodium as a coolant simplifies the model design and allows one to use reliable widely spread measurement tools, in particular, optical velocimetry systems.

Reactor models can be conditionally separated into two groups by the way of water circulation: open and closed ones. Water is supplied to an open system by pumping from vessels containing "hot" and "cold" water (the temperature difference can reach 70°C). When the reactor operation is modeled, "hot" and "cold" water is simultaneously supplied to the model operating in the power mode. When shutdown-cooling modes are simulated, water is supplied to the model in a sequence: first "hot" and then "cold" water [4, 5].

As a rule, open models are used to study the operation of the reactor fragments, for example, the upper or lower plenums of the reactor [6]. Such models are suitable for investigation of steady-state power operation modes, however, the application of plenums imposes certain limitations on the testing mode duration.

Closed models include the main elements of the reactor: the core, the heat exchangers, the upper and lower reactor plenums, and so on [7–9]. Water is heated in electric heaters of the core model and then cooled in the heat exchanger models by heat exchange between the circuits. Natural circulation occurs in the core model due to the temperature difference. When steady-state power operation modes of the reactor are simulated, the average heating in the core model is approximately 10°C. Closed models are used to study long-term reactor cooling modes.

The processes in the intermediate and air circuits of the DHR system are simulated using different methods. In some test facilities, these circuits are connected to a relatively simple reactor model [9]. The application of the water–air heat exchanger for simulation of the processes in the air circuit results in the fact that the temperature drop in the heat exchanger makes a major part of the available temperature difference in the whole DHRS loop model. As a result, heating in the first and intermediate circuits is just 10°C [9]. In some test facilities, the intermediate and air circuits of the DHR system are not simulated, main attention is paid to the processes in the reactor, and the studies imply quite complicated reactor models [8].

TISEY TEST FACILITY

The TISEY test facility is designated for investigation of thermohydraulic processes in a fast reactor and DHRS. The test facility includes a closed model of the fast reactor with an intermediate DHRS circuit. An air circuit is not simulated. The test facility simulates the nominal reactor operation mode and the modes of cooling via the DHRS.

It was established by analysis of data [8, 10] that similarity with respect to just several criteria can be provided by the reactor simulation, which makes it impossible to extrapolate the experimental results from the model to a real reactor. Heat exchange in sodium cannot be studied using water test facilities (due to the difference in the Prandtl numbers for these liquids by several orders of magnitude). Experiments at reactors and test facilities with sodium are required for this purpose. Therefore, complex verification of numerical codes using experimental data with subsequent DHRS calculation with these codes is necessary.

The problems of simulation of thermohydraulic processes are considered in [10].

The main linear dimensions (outer contours and elevation marks of the equipment) in the model are reduced by a factor of five as compared to a reactor. The total height of the test facility is 21 m. One loop of the reactor heat exchange, namely, a sector with an opening angle of 80°, is simulated. The maximum power of the core model when simulating the reactor power operation mode is 350 kW, and that for simulation of the cooling mode is 70 kW.

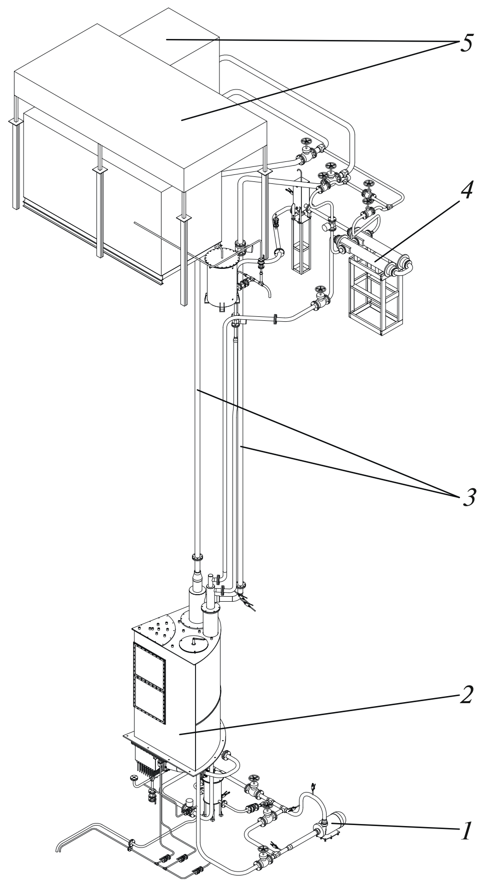

Fig. 1. View of TISEY test facility: (*1*) is the pump P-1 of the first circuit; (*2*) is the reactor model; (*3*) are the pipelines; (*4*) is the AHX; (*5*) is the cooling installation with the pump P-2 of the cooling circuit.

The view of the test facility is shown in Fig. 1 (the support structures and the electric equipment are not shown). The test facility includes the first circuit (the reactor model), the intermediate circuit, and the circuit of cooling the models of the intermediate (IHX) and air (AHX) heat exchangers. Water is used as a coolant.

When the nominal reactor operation mode is simulated, water circulation in the first circuit is provided by the pump situated beyond the reactor model. Heat exchange between the circuits is performed in the IHX, DHX, and AHX models. The AHX is cooled by pumping water instead of air that is used in a standard DHRS. The final coolant of the test facility is air circulating through a cooling unit that includes the pump of the second cooling circuit (P-2).

The model of a fast reactor is shown in Fig. 2. The vessel has transparent windows for optical velocimetry. The reactor model is thermally insulated by mineral wool.

When the pump P-1 is switched on, the valve is closed, water is supplied via a special pipeline from the displacer to the P-1 inlet and then to the high-pressure plenum. The DHX model is connected with the high-

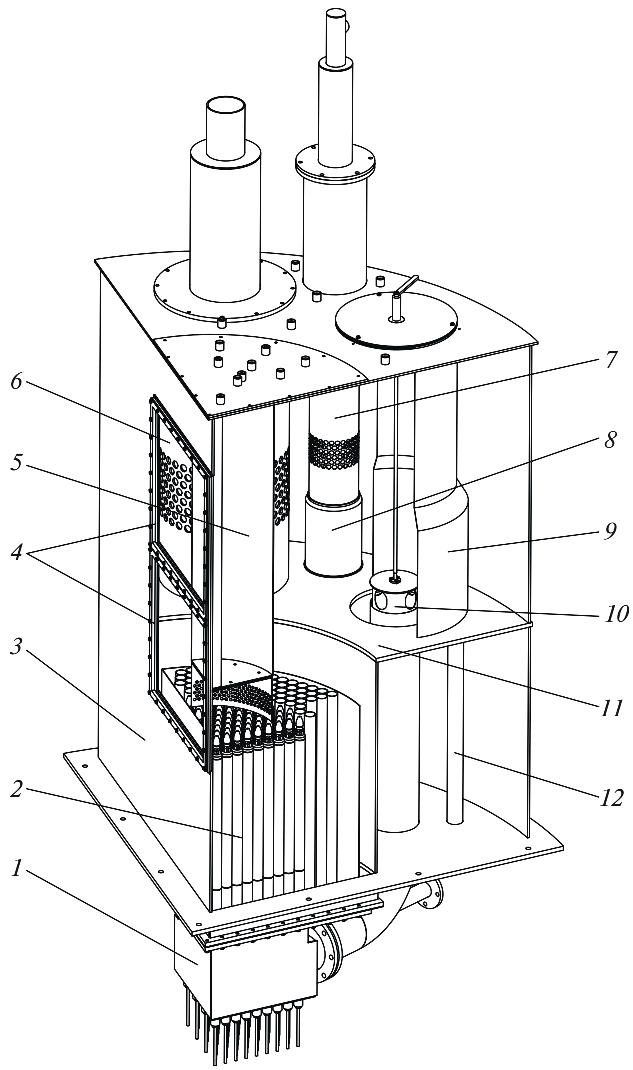

Fig. 2. Model of a fast reactor: (*1*) is the high-pressure plenum; (*2*) is the core; (*3*) is the vessel; (*4*) are the windows; (*5*) is the displacer of the central rotation column; (*6*) is the IHX; (*7*) is the DHX; (*8*) is the shield; (*9*) is the PP-1 displacer (part of the displacer is shown); (*10*) is the valve; (*11*) is the support ring; (*12*) is the pipeline.

pressure plenum by a special pipeline. In the cooling mode, a shell forming a channel for water supply to the pipeline and then to the high-pressure plenum is installed at the DHX outlet. The check valve is installed in the lower part of the DHX (not shown in Fig. 2).

The core of the reactor model represents a group of 63 electrically heated SA simulators separated into three sections and 67 non-heated simulators of spent SAs, side shielding assemblies. The simulators of the three sections differ by hydraulic resistance and the power of the heaters. Each SA simulator includes seven tube-shaped electrical heaters with an external diameter of 12 mm and an active part length of 0.4 m. The maximum SA simulator power is 8.5 kW. Water from the high-pressure plenum is not supplied to non-heated simulators of spent SAs.

Information accumulation and primary processing is performed using an information and measurement system (IMS) of the test facility. Table 1 gives the data on primary transducers included in the IMS. The power of the core model is controlled using special autotransformers that allow one to measure the active power with high precision. The flow meter installed on the DHX pipeline measures the water flow rate in the forward and backward directions. The IMS is used to record all the test facility parameters; the recording rate varies from 1 to 10 Hz.

The two components of the water velocity field are measured in the upper plenum of the reactor model. For this purpose, an optical particle image velocimetry system [11, 12] specially developed at the Institute of Applied Physics (Russian Academy of Sciences) is used.

The essence of the velocity measurement method is as follows. Particles are added to the water of the first circuit and the flow is illuminated through the windows in the reactor model by the laser knife and recorded by video cameras. The time sequence of images is subject to cross correlation processing for finding the velocity field at the nodes of the given coordinate grid. Information is written discretely. Each record of the testing mode consists of a group of sub-records with a duration from 7 to 10 s. Each record of the testing mode consists of the recording phase with a duration of 2 s (when the recording is performed with a rate of 50 frames/s) and the phases of information transmission and storage.

EXPERIMENTAL RESULTS

The parametric studies of the mode of reactor cooling via DHRS were performed at the TISEY test facility. We adjusted the power of the core model and the DHRS, the level of the liquid in the reactor model, the position of fittings, etc. Several versions of the DHRS design were studied.

Table 2 gives the characteristics of some testing modes. In modes RD01, RD02, and RD16, the new version of the DHRS design with the DHX check valve was studied when the valve in the PP-1 was opened at different time instants. In these modes, water from the upper plenum of the reactor was supplied to the DHX, being cooled by the water of the intermediate DHRS circuit, and then along the DHX pipeline to the high-pressure plenum, into spent SAa, and back to the upper plenum.

The DHRS version without a DHX check valve (closed valve) was studied in the RD08 mode. In this mode, water from the upper plenum was supplied to the DHX, cooled, and then supplied back to the upper plenum, and then went along the plate of the support ring from the DHX to the core. At the periphery of the core, part of the water from the DHX was mixed with

Table 1. Data on primary transducers

Parameter	Primary measurement transducer	Number, pcs.	Error, not higher than
Temperature	Chromel Copel thermocouple with uninsulated junction with a diameter of 1 mm (OKBM)	532	0.4°C
Flow rate	Electromagnetic flowmeter system Promag 50P (Endress+Hauser Flowtec AG, Germany)	5	3.0%
Pressure, pressure drop, level	Pressure and pressure drop transducer Sapfir 22R (JSC Teplopribor, Ryazan)	14	3.0%
Active power	Voltage and current transducers E 855/1-M1, E 854/1-M1 (LLC Energosoyuz, Republic of Belarus)	6	3.0%

Table 2. Characteristics of the testing modes

Characteristic	Mode				
	RD01	RD02	RD08	RD14	RD16
Shield at DHX outlet	Yes	Yes	No	No	Yes
Position of DHX check valve	Opened	Opened	Closed	Opened	Opened
Position of valve in PP-1 displacer	″	Closed	Opened	″	″
Time instant of valve opening in PP-1 displacer, s	210	—	210	210	60

Table 3. Sequence of operations

Notation	Time, s	Operation
A1	0	Reduction of core power from 1.00 to 0.22 arb. units
B	60	Switching off P-1 pump, opening DHX check valve (except RD08 mode)
C	60 or 210	Opening valve in PP-1 displacer (except RD02 mode)
D	70	Switching off P-2 pump
E	100	Switching on P-2 pump for supplying water to AHX
A2	300	Reduction of core power to 0.14 arb. units
A3	800	Same, to 0.12 arb. units
A4	1500	Same, to 0.09 arb. units
A5	5000	Same, to 0.06 arb. units

the water flow from the core, and the remaining part was supplied to the space between spent SAs.

Cooling of the reactor with the opened DHX check valve without a shield was studied in the RD14 mode. For this DHRS design in the case of a hypothetic failure of the DHX check valve, the output DHX window is not closed. In this model, part of the water from the DHX was supplied to the DHX pipeline, and the remaining part was supplied to the upper plenum of the reactor.

The power operation of the reactor in the initial state was simulated. The reactor cooling mode simulation began from the step-wise reduction of the core model power from 1.00 to 0.22 arb. units. Then, the power was reduced by a factor of four, which simulated the reduction of residual heat release. Mechanical runout of the pumps in the standard facility was simulated by delay in the pump switching off: the pump P-1 was switched off for 60 s, and the pump P-2 for 70 s. Simultaneously with switching off the pump P-1 in all modes, except RD08, the DHX check valve was opened. In a time interval from 70 to 100 s, the fittings in the cooling circuit were switched. As a result, cooling water was supplied to the AHX, which simulated the development of natural circulation in the air circuit of the standard DHRX. In all modes, except RD02, the valve in the PP-1 displacer was opened. The time instants of the valve opening are given in Table 2, and the total sequence of operations is given in Table 3.

The variation of the relative water flow rate for the first and intermediate circuits (divided by the constant flow rate of cooling water through the AHX) through

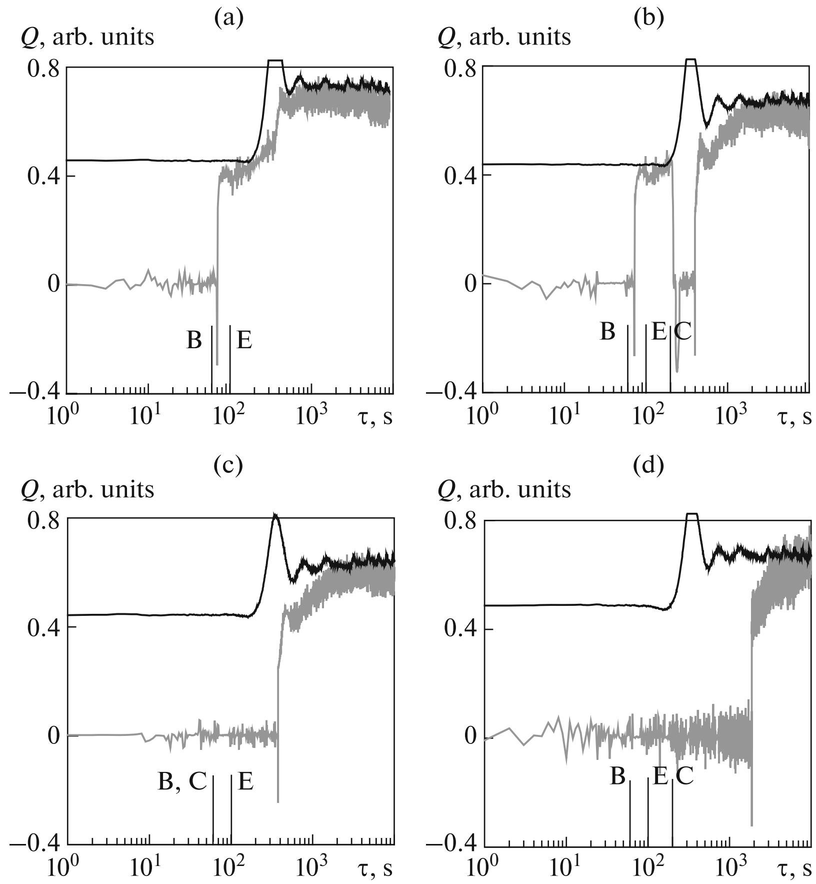

Fig. 3. Relative water flow rate through the DHX model from (grey lines) the first and (black lines) intermediate DHRS circuits in the following modes: (a) RD02, (b) RD01, (c) RD16, (d) RD14.

the DHX in the RD01, RD02, RD14, and RD16 modes is shown in Fig. 3 (letters indicate operations according to Table 3). It can be seen that the flow rate evolution strongly depends on the position of the valve in the PP-1 displacer. For the closed valve in the RD02 mode, the flow rate increases first to 0.40 arb. units and then to 0.65 arb. units. In the RD01 mode, when the valve is opened at a time instant of 210 s, the reversal and termination of natural circulation through the DHX takes place, and, then, the water flow increases smoothly. In the RD16 mode, when the valve is opened at a time instant of 60 s, no circulation reversal through the DHX occurs. In all modes, the flow rate through the DHX increases at a time instant of 400 s, which is determined by the DHX cooling by the water of the intermediate DHRS circuit. In the RD14 mode, in spite of the absence of a shell, water from the DHX begins to come to the DHX pipeline at a time instant of approximately 2000 s. In this mode, part of the water from the DHX flows to the DHX pipeline and, then, into the spent SAs, while the remaining part flows to the upper plenum of the reactor.

Figure 4 shows the variation of excessive water temperature ϑ at the inlet and outlet of spent SAs for three sections of the core in the RD01 and RD08 modes. The excessive temperature $\vartheta = t - t_{\text{cool}}$, where t is the time-averaged value of the temperature at the point of measurement, °C; t_{cool} is the time-averaged value of the cooling water temperature at the AHX inlet, °C (the temperature is maintained constant during the whole testing mode).

In the RD01 mode, water was supplied to the high-pressure plenum of the reactor via the IHX and DHX. According to our numerical estimates, in this mode, the flow rate through the IHX is higher at the initial cooling stage than that through the DHX, and the flow rate through the IHX decreases smoothly to zero, while the flow rate through the DHX increases (see Fig. 3). At a time of approximately 800 s, the flow rate through the DHX was several times higher than the flow rate through the IHX (the flow rate through the IHX was not measured), the water temperature at the spent SAs inlet was nearly equal to the water temperature at the DHX outlet.

In the RD08 mode, the water was supplied to the high-pressure plenum through the AHX alone. The water from the PP-1 displacer, heated by the water in the upper plenum of the reactor, was supplied along

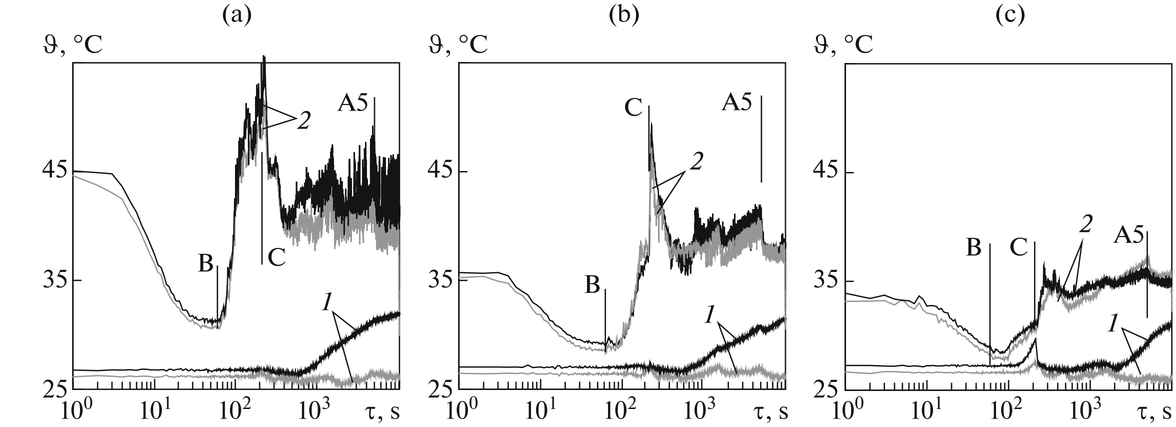

Fig. 4. Excessive water temperature (*1*) at the inlet and (*2*) outlet of spent SAs for the (a) first, (b) second, and (c) third sections of the core model. The testing modes are (grey lines) RD01 and (black lines) RD08.

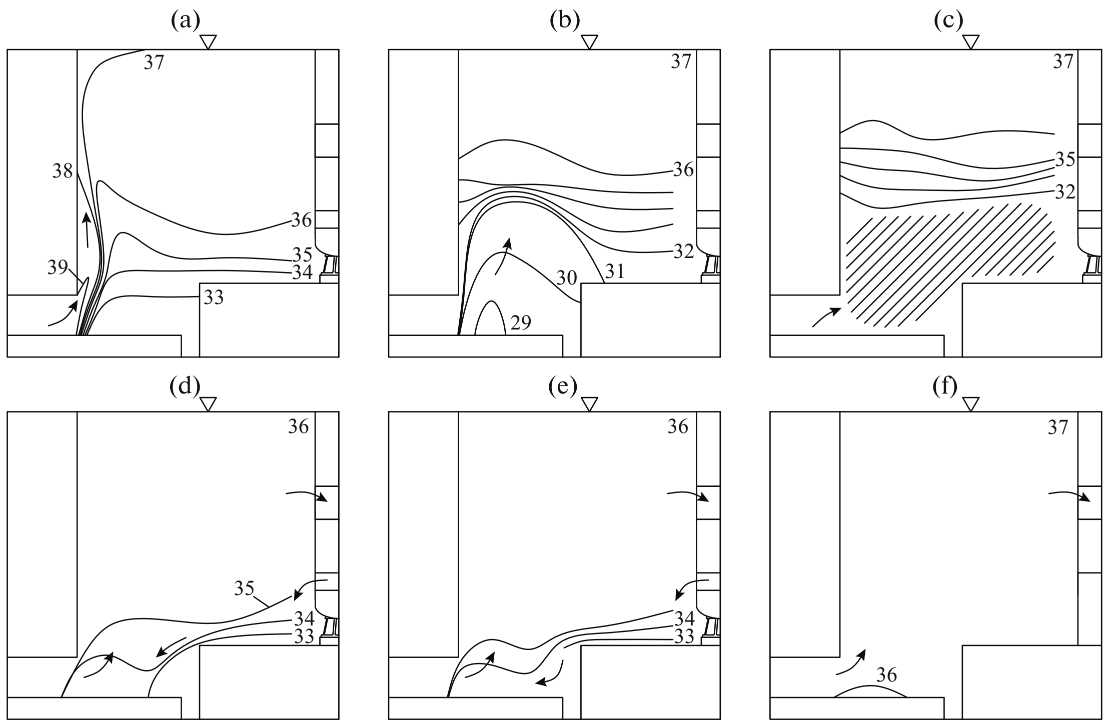

Fig. 5. Excessive water temperature, °C, in the upper plenum of the reactor in the RD08 mode for the following time instants, s: (a) 0, (b) 55, (c) 120, (d) 600, (e) 9000; and (f) in the RD01 mode for a time instant of 9000 s.

this line to the high-pressure plenum. The water supply from the PP-1 displacer resulted in the temperature growth at the inlet of spent SAs.

Figure 5 shows the fields of excessive water temperature in the upper plenum of the reactor in the direction toward the DHX for different time instants in the RD01 and RD08 modes (arrows show the typical water flows). Figure 5 shows the data for the RD01 mode in a time interval from 0 to 600 s, since the temperature fields in both modes are approximately the same at the initial cooling stage. In the initial state (see Fig. 5a), the water flow goes from the core along the central rotation column displacer, and temperature stratification of the liquid is observed along the height of the upper plenum. When the PP-1 rundown is simulated, water from the lower plenum is supplied to the upper plenum, which results in higher temperature gradients (see Fig. 5b). After the pumps P-1 and P-2 are switched off, high-intensity liquid mixing takes place in the lower part of the plenum (dashed region in Fig. 5c). After the DHX is cooled by the water of the

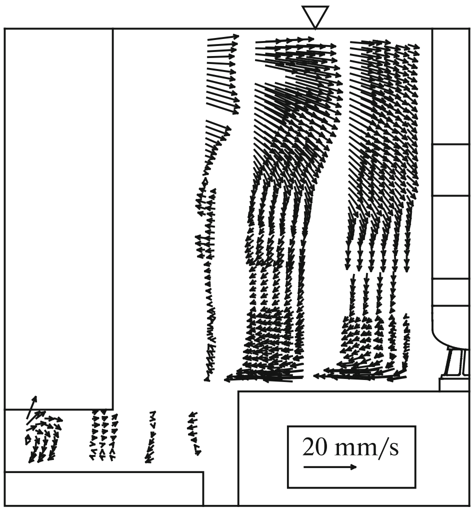

Fig. 6. Water velocity field in the upper plenum of the reactor model in the RD08 mode for a time instant of 4000 s.

intermediate circuit, natural circulation of the first circuit water through the DHX develops (see Figs. 5d, 5e).

At the stage of quasi-stationary cooling (see Figs. 5e, 5f) the fields of excessive temperature in the two modes differ substantially. In the RD08 mode, the water supplied to the upper plenum of the reactor from the DHX flows along the support ring, which determines the temperature gradient above the support ring. In the RD01 mode, the water from the DHX is supplied to the DHX pipeline and then to the high-pressure plenum, and the water temperature is hardly changed in the volume of the upper plenum of the reactor. It was estimated from the DHX thermohydraulic parameters that, in the RD01 mode, approximately 86% of the DHX power is removed by water convection through the tube bundle, and the remaining 14% of the power is removed by exchange through the DHX barrel.

Figure 6 shows the water velocity field in the upper plenum of the reaction in the direction toward the DHX in the RD08 mode for a time instant of 4000 s. High intensity flow of the water supplied to the upper plenum from the DHX can be clearly seen along the support ring, which agrees with the results of measurement of the temperature fields.

Figure 7 shows the variation of excessive water temperature along the height of the lower plenum of the reactor (from the IHX to the PP-1 displacer) at different time instants in the RD01 mode. In the initial state (see Fig. 7a), the temperature field is inhomogeneous, which qualitatively agrees with the data obtained for operating BN-600 and BN-800 reactors. The water supply from the IHX to the lower plenum (see Fig. 7c) results in strong gradients and pulsations of temperature in the lower part of the plenum. It follows from the linear law of water temperature variation along the plenum height (see Fig. 7e) that heat exchange in the liquid goes mainly via heat conduction at the stage of quasi-stationary cooling.

CONCLUSIONS

(1) Testing at the TISEY test facility experimentally proved the efficiency of the new cooling method for an advanced fast reactor via a DHX check valve. After passive opening of the DHX check valve in the reactor model, natural circulation through the DHX was obtained, while circulation through the IHX was observed at the initial stage of cooling only.

(2) The position of the valve in the PP-1 displacer and the time instant of its opening influence the development of natural circulation via the DHX from the reactor side: in the case of the closed valve, circulation through the DHX develops immediately in the for-

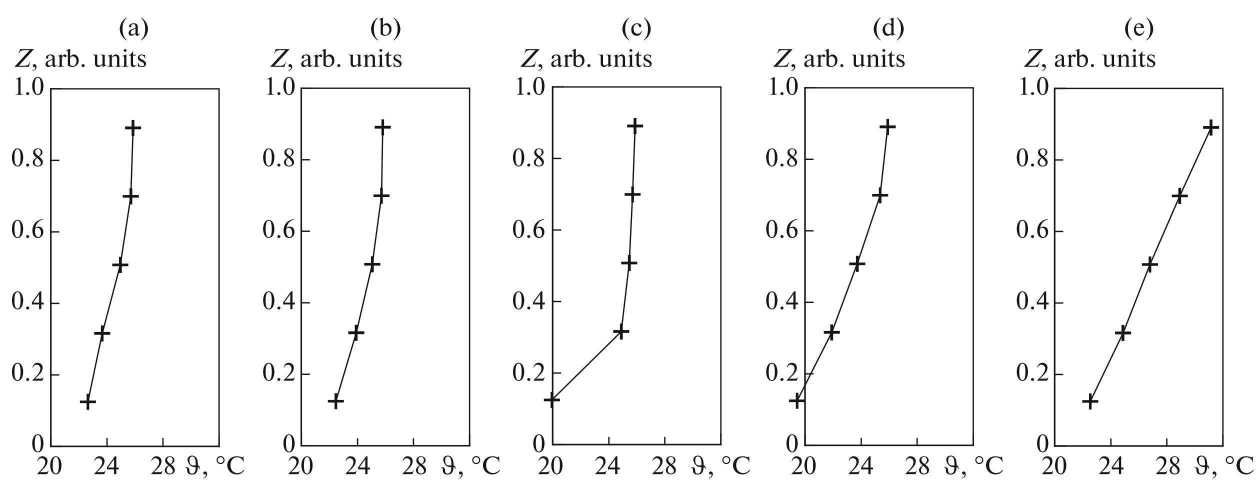

Fig. 7. Excessive water temperature, °C, (isotherms) in the lower plenum of the reactor in the RD01 model for the following time instants, s: (a) 0, (b) 60, (c) 120, (d) 600, (e) 9000; *Z* is the vertical coordinate in the upward direction.

ward direction, while, if the valve opens with a delay, it is first reversed, and, then, stable natural circulation in the forward direction through the DHX develops.

(3) The possibility of the reactor cooling via an open DHX check valve without a shield at the outlet was experimentally proved. This DHX design ensures efficient cooling in the case of a hypothetic failure of the DHX check valve opening.

(4) The data on the temperature and velocity fields in the reactor model obtained in the tests are used for adjustment of 3D numerical models.

REFERENCES

1. *Fast Reactor Database 2006 Update*, IAEA Technical Document No. 1531 (IAEA, 2006).
2. A. V. Zhukov, A. P. Sorokin, and Yu. A. Kuzina, "Emergency cooling down of fast-neutron reactors by natural convection (a review)," Therm. Eng. **60**, 345–354 (2013). doi 10.1134/S0040601513050108
3. D. G. Zaryugin, V. M. Poplavskii, V. I. Rachkov, A. P. Sorokin, Yu. E. Shvetsov, S. A. Rogozhkin, and S. F. Shepelev, "Computational and experimental validation of the planned emergency heat-removal system for BN-1200," At. Energy **116**, 271–277 (2014).
4. A. N. Opanasenko, V. M. Selivanov, and N. N. Shan'gin, "Effect of unsteady natural convection on the structure of a liquid flow in the horizontal mixing chamber," Inzh.-Fiz. Zh. **39**, 603–610 (1980).
5. J. J. Lorenz and P. A. Howard, "Entrainment by a jet at a density interface in a thermally stratified vessel," J. Heat Transfer **101**, 538–542 (1979).
6. D. Tenchine, "Some thermal hydraulic challenges in sodium cooled fast reactors," Nucl. Eng. Des. **240**, 1195–1217 (2010).
7. D. G. Zaryugin, S. G. Kalyakin, S. T. Leskin, A. N. Opanasenko, and A. P. Sorokin, "Numerical and experimental investigations of thermalhydraulic characteristics for fast reactor vessals on integral model SARH in different operation regimes," Izv. Vyssh. Uchebn. Zaved., Yad. Energ., No. 2, 96–104 (2013).
8. D. Weinberg, K. Rust, and H. Hoffmann, *Overview Report of RAMONA-NEPTUN Program on Passive Decay Heat Removal* (Forschungszentrum Karlsruhe, 1996). http://bibliothek.fzk.de/zb/berichte/FZKA5667.pdf.
9. D. Wilhelm, G. Hansen, and H. Strotmann, "The 1 : 10 scale chain of natural convection "KIWA" for studying the LMR passive decay heat removal," in *Proc. Int. Conf. on Design and Safety of Advanced Nuclear Power Plants (ANP'92), Tokyo, Japan, Oct. 25–29, 1992* (At. Energy Soc. of Japan, 1992), Vol. 3, Paper 26.4.
10. V. V. Pakholkov, A. I. Potseluev, S. A. Rogozhkin, and S. F. Shepelev, "Experimental studies of BN reactor cooling modes on a thermal-hydraulic test facility "TISEY"," in *Proc. 18th Int. Conf. for Young Specialists on Nuclear Power Plants* (Gidropress, Podolsk, 2016). http://www.gidropress.podolsk.ru/files/proceedings/kms-2016/documents/kms2016-035.pdf.
11. D. A. Sergeev, "A measuring system for studying liquid flows by the particle image velocimetry method based on a diode-pumped solid-state laser," Instrum. Exp. Tech. **52**, 438–444 (2009).
12. D. A. Sergeev, A. A. Kandaurov, Yu. I. Troitskaya, V. V. Pakholkov, S. A. Rogozhkin, and S. F. Shepelev, "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," Instrum. Exp. Tech. **60**, 418–427 (2017).

Translated by E. Baldina