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EXPERIMENTAL STUDY OF DEPARTURE FROM NUCLEATE BOILING ON THE SURFACE OF A MOLTEN CORE CATCHER UNDER CONDITIONS OF BOILING BORATED WATER WITH DEBRIS

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The results of an experimental study associated with the departure from nucleate boiling flux on the surface of a flat plate in the absence of a directional movement of borated water burdened with debris are presented. The experiments model the external surface cooling of a water-water energy reactor molten core catcher in the case of a severe accident involving the destruction of the reactor vessel. The obtained data showed that critical heat flux can be approximately a quarter lower for debris-burdened water than for pure process water under the same conditions. At elevated temperatures, debris components containing epoxy resin particles adhere to surfaces to impair heat transfer.

According to the safety concept of a water-water energy reactor (WWER) NPP, an important role is played by the retention of the melt in the casing of the molten core catcher (MCC) in severe accidents involving core melting. Heat removal from the external surface of the MCC casing is carried out when the cooling water boils under conditions of a large coolant volume. One of the basic criteria determining the reliability of the heat removal consists in the margin to the departure from nucleate boiling (DNB) in a large volume of water contaminated with boric acid and weighed undissolved particles of various compositions, i.e., debris. Under the impact of coolant jets flowing from a rupture in the primary circuit pipeline, such debris is formed from the heat insulation and protective coatings of pipelines and equipment, as well as during the washing of latent debris from the surfaces of the containment and equipment.

Semi-empirical dependencies obtained for pure process water are currently used to estimate the DNB margin when boiling occurs in a large coolant volume. However, experimental data and design recommendations for water contaminated with the debris and boric acid are absent. In order to obtain such data, the Korvet-2 experimental plant was created to model the thermal-hydraulic processes of boiling in the external cooling circuit of the MCC casing with the reproduction of full-scale thermodynamic parameters (Fig. 1). The main technical characteristics of the experimental plant are as follows:

Height of the water column in the circulation circuit, m	Up to 10
Coolant pressure at a zero elevation, kPa	Up to 200
Supplied electric power, kW	Up to 180
Heat flux density of the working section, MW/m^2	Up to 2.8

The plant includes the following main units and systems: model of MCC shaft comprising a duct with vertical and inclined working sections; model of the sections of the conical and cylindrical MCC casing surface; coolant circulation circuit; measurement system.

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TABLE 1. Measuring Transducers

Measured parameter	Sensor type	Error
Water temperature	Resistance thermometer	$\pm(0.1 + 0.0017t)$, °C*
	Thermocouple	±1.5°C
Plate temperature	Thermocouple	±1.5°C
Fluid displaced level	Differential pressure sensors	±1.6 kPa
Measurement of differential pressure at the duct outlet	Differential pressure sensors	±0.04 kPa
Electrical power	Acquisition device	±1.5%
Debris mass	Electronic scales	$\pm10^{-3}$ kg

* Measured temperature *t*.

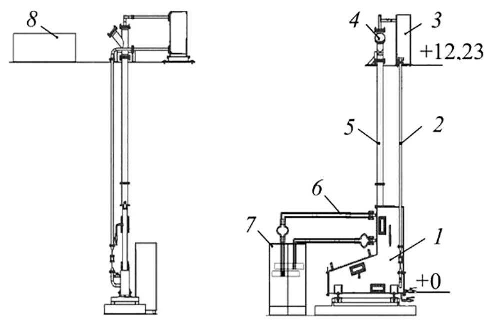

Fig. 1. Korvet-2 experimental plant: *1*) duct with working sections; *2*, *5*) lowering and lifting sections, respectively; *3*) condensing heat exchanger; *4*) strainer; *6*) current-conducting buses; *7*) rectifier; *8*) make-up tank.

The duct represents a steel container with a volume of ~0.3 m^3 insulated from the outside. The movement of the coolant with the debris is observed through three transparent windows in the area of working sections. The design of the duct provides for removable flange-type elements to install and fix working sections, plugs, and pipelines. The coolant is heated at the bottom of the duct. The duct comprises vertical working sections of 0.5 m length and 5 mm thickness, as well as sections inclined by 16° with a length of 1 m and thickness of 10 mm, representing rectangular plates made of corrosion-resistant steel, 0.1 m wide, which correspond to the cylindrical and conical surface of the CMM casing.

The circulation circuit ensures heat removal from the working sections of the duct in gravity circulation mode. In addition, using manual globe valves along with control and measuring equipment, it performs and control the processes of the coolant filling and discharge, maintenance of the assigned parameters, as well as filtration and vapor condensation.

The measurement system, whose parameters are described in Table 1, includes primary transducers, secondary transducers, data acquisition devices, as well as a server for recording and processing experimental data.

The complexity and risks involved in the experiments, including possible decompression of the circulation circuit due to condensation shocks and burnout of electrically heated plates during the DNB, required the creation of an automated system for switching off the electric heating according to the readings of local temperature sensors. A high-speed camera was used to record video of coolant boiling modes in the MCC model through special windows.

Experimental procedure. Debris components were preliminarily processed (Table 2) by subjecting a super-thin basalt fiber to thermal aging at 280°C for 2.5 h and grinding. DNB experiments under the boiling of the debris-laden boric acid solution were carried out as follows. The experimental plant was filled with water to a level corresponding to the program-set pressure of the coolant at the lowest point of the working section. For example, in experiments with a pressure of 100 kPa, the water level from the bottom of the duct varied in the range of 1.7–1.8 m. Debris components and boric acid were poured into the coolant in amounts specified by the experimental program. The quantity of debris and boric acid components was determined based on the required mass of the water in a particular experiment. Next, the water was mixed with the debris

TABLE 2. Debris Components

Debris material	Concentration in the solution, g/L
Super-thin basalt fiber	3.6
Fine sand	0.3
Clay	0.3
Thermosetting varnish-and-paint material	2.7
Zinc oxide	5
Aluminium hydroxide	0.4

by bubbling air to the perforated collector at the bottom of the duct for several minutes. Then, a voltage supplying the rectifier and additional electric heaters in the duct for setting the necessary temperature close to that of coolant saturation were switched on. Temperature values were recorded according to the readings of temperature sensors installed in the duct. After the beginning of coolant boiling in the duct, additional heaters were switched off. Then, the coolant was again stirred to a homogeneous state.

With the beginning of the active phase of the experiment, DC power was increased in several stages using the rectifier. A consecutive increase in the power was carried out within 3–5 min following stabilization of the working section plate temperature. The step of the power increase was within 5–10% of the previous one.

The DNB was recorded according to thermocouple readings (a sharp increase in the plate temperature). In addition, for reliable DNB control over the entire surface of the plate and to prevent its burning, the temperature of the plate external surface was visually controlled according to the readings of the thermal imaging camera. The heat flux from the surface of the working section to the coolant was calculated as the ratio of the DC power flowing through the cross-section of the heated working section plate to the contact area between this plate and the coolant. The average heat flux of pre-DNB and DNB power increase stages was taken in terms of a DNB flux. The mode parameters of the coolant pressure and temperature were similarly averaged.

Upon the completion of each experiment, following the discharge of the coolant from the plant circuit, deposits of boric acid and debris components were cleaned from the electrically heated plates, MCC models, and other circuit elements.

Experimental results. The experiments were carried out using process water without impurities, as well as with the addition of boric acid and debris (Table 3). The experiments showed that boration of the water in the studied concentration range had no noticeable effect on the DNB flux obtained under the same conditions using pure process water.

The analysis of experimental data is based on the formula for DNB flux under boiling conditions in a large volume of the coolant*

$$q_{\mathrm{DNB}} = Kr(\rho'')^{1/2}[g\sigma(\rho' - \rho'')]^{1/4}, \tag{1}$$

where K – Kutateladze parameter; r – latent heat of vaporization (J/kg); ρ', ρ'' – saturation densities of water and vapor, respectively (kg/m^3); $g = 9.812$ – acceleration due to gravity (m/s^2); σ – surface tension coefficient (N/m).

According to Fig. 2, the DNB in experiments with pure process water and borated water with debris on a vertical surface can be described by Eq. (1) at $K = 0.12$ and $K = 0.11$, respectively, i.e., the influence of the debris in this case is insignificant.

Analogous data given in Fig. 3 for the inclined plate shows the significant influence of the debris on the DNB flux: the generalizing parameter K for the working section with the pure process and debris-laden water is equal to 0.062 and 0.044, respectively.

According to the observations, the adhesion of debris occurs at the surface temperature at which the protective coating particles (epoxy paint) in contact with the surface become melted and starts to adhere to the metal (Fig. 4). Then, other components of the debris adhere to these paint particles resulting in a gradual thickening of the sediment layer on the surface. In the experiments, the thickness of the debris adhesion layer was 0.1 mm.

* S. S. Kutateladze, *Fundamentals of Heat Exchange Theory*, Atomizdat, Moscow (1979).

TABLE 3. Experiments

Parameter	Section	
	Vertical	Inclined
	Number of experiments	
	Pure process water	
Pressure, kPa:		
1.1	3	3
1.5–1.6	8	4
1.9–2	7	3
	Boric acid solution (P ~ 100 kPa)	
Boric acid concentration, %:		
0.4	3	3
0.8	3	3
1.2	3	3
1.6	5	3
3.5	1	–
5	1	–
	Borated water with debris (boric acid concentration ~ 1.6%)	
Pressure, kPa:		
1.1	3	3
1.5–1.6	6	3
1.9–2	6	3

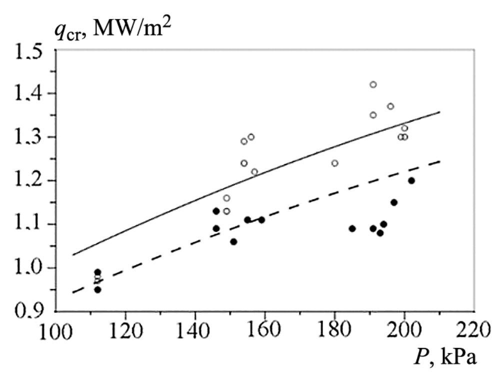

Fig. 2. DNB flux for the vertical plate in the experiment with the pure process (○) and debris water (●), described according to Eq. (1) at the parameter K equal 0.12 (——) and 0.11 (– – –), respectively.

Conclusion. The studies of the DNB during the boiling of borated water on 0.5–1 m long vertical and inclined surfaces at a pressure of 100–200 kPa establish no effect of the boric acid concentration in the process water (up to 5 and 1.6% for the vertical and inclined plate, respectively) on the DNB flux.

In the experiments with debris-laden borated water, the DNB flux on the vertical surface is reduced by ~9% as compared to the experiments with pure process water. For the inclined surface, the value decreased by ~25%. The reason for this involves the adhesion of debris components to the surface of the plates. The adhesion occurs during the melting of epoxy resin particles representing a component of containment coatings. Further enhanced research on this debris component is required.

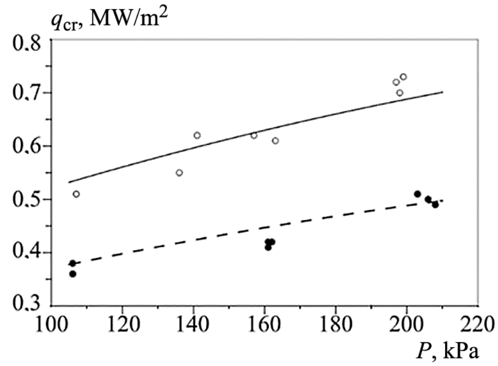

Fig. 3. DNB flux for the plate with the inclination angle of 16° in the experiment with the pure process (○) and debris water (●), described according to Eq. (1) at the parameter *K* equal to 0.062 (——) and 0.044 (– – –), respectively.

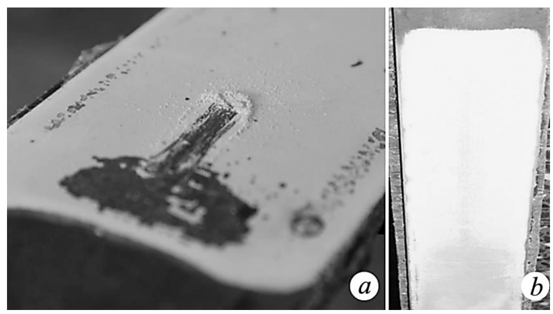

Fig. 4. Surface of the vertical (*a*) and inclined plate (*b*) in the experiment with the debris-laden water.

Experimental data and calculated recommendations can be used for the fulfillment of design works to evaluate the influence of coolant contamination on the emergency cooling of the MCC casing.