INVESTIGATION OF TWO-PHASE FLOW STRUCTURE IN MODEL OF DRAUGHT PIPE OF WATER BOILING REACTOR VK–300

EFANOV A. D., KUZNETZOV YU. N., KALIAKIN S. G., LISITZA F. D., REMIZOV O. V., SERDUN' N. P.

IPPE, Obninsk, Russia

KEYWORDS: VK-300 reactor, thermal hydraulics, void fraction

INTRODUCTION

VK-300 reactor represents a vessel-type boiling reactor with integral arrangement of assemblies and in-vessel steam separation at one-circuit scheme. The circuit consists of core, draught pipes, and separation facilities. The vessel of VK-300 reactor is chosen on the base of the dimensions of that of VVER-1000 reactor.

Description of the VK-300 reactor construction in details and the principles put on its base are presented in [1].

STATEMENT OF THE PROBLEM

The following thermal-hydraulic parameters of nuclear power plant (NPP) were investigated experimentally:

- dependence of void fraction upon the steam quality in mixing chamber (on the draught section input);
- pressure losses at different, specific zones of up-flow and down-flow sections of the circuit with free circulation;
- degree of steam separation in the separating chamber (at the first step of phase separation) and its dependence upon steam quality.
- structure of steam-water flow in draught pipes (distribution of phases over the draught pipe cross-section);
- presence of steam hovering and height of this hovering in inter-pipe space of draught section;

MODEL OF REACTOR FACILITY

As a model of NPP, for the above mentioned thermal-hydraulic parameters to be investigated, the solitary draught pipe was used. The sizes of test section were chosen such as equivalent flow cross-sections of draught pipes, mixing and separating chambers per one draught pipe. Coefficient of volumetric-power simulations was equal to the ratio of the areas of flow cross-section of these circuit elements for natural and model facilities and was equal

$$K_{mod} = \frac{S_{nat}}{S_{mod}} = 2.37.$$

Such choice of the model is stipulated by the following reasons. The draught section of reactor represents a system of draught pipes, in which the similar thermal-hydraulic processes take place.

Thus, the meanings of thermal-hydraulic parameters obtained on one pipe, can be spread on the others ones, but it is possible to take into account thermal-hydraulic difference of different draught pipes by carrying out the measuring at different values of steam quality and flow-rate.

Height of natural and model facility from the core output lattice to the axial separators input (up to submerged leaf) are also the same.

As a power source the heat-electric plant was used; and steam-water mixture with necessary composition and flow-rate was prepared in the volumetric mixer from boiler nutritious water and superheated steam from drum-separators.

RANGE OF STUDIED PARAMETERS

The experiments were carried out at the following regime parameters:
The steam-water mixture flow-rate at the test section input:

$G_{mix} = 0.5G_{nom}$;
$G_{mix} = 1.5G_{nom}$;
$G_{mix} = G_{nom}$;

Nominal flow-rate of steam-water mixture in the draught pipe model:

$G_{nom} \cong 35$ tons/hour (10 kg/s);

Steam quality at the test section input:

$x_{in} = -0.05 \div 0.20$;

The step of steam quality change:

$\Delta x = 0.05$.

The pressure in these experiments was supported as $P \approx 3.3 \div 3.5$ MPa; it was equal to the operating pressure in the boilers of SSC RF-IPPE heat-electric plant.
The analysis of data published in literature [2 – 4] made it possible to conclude that steam-water flow structure in draught pipe does not depend upon the pressure in the range of $3.0 \div 7.0$ MPa. The influence of pressure upon the other thermal-hydraulic parameters when transferring experimental data for natural NPP can be taken into account by dependence of physical properties on pressure.

CONSTRUCTION OF TEST SECTION

Schematically, construction of test section is shown in Fig. 1. The base of the test section is a body 1, inside which all the circuit elements are located.
The coolant (water or steam-water mixture from mixer) flows through output lattice 2 to mixing chamber 4, restricted in its upper part by leaf 3. The draught pipe 6 rests on an output lattice. Three holes are made in the output lattice, so that some quantity of the coolant hits immediately inside the draught pipe, and another part – in inter-pipe space of mixing chamber 4, and then inside the draught pipe through windows 5 on its lateral surface. This assembly imitates completely the natural construction. The length of draught pipe is of 2.054 m.

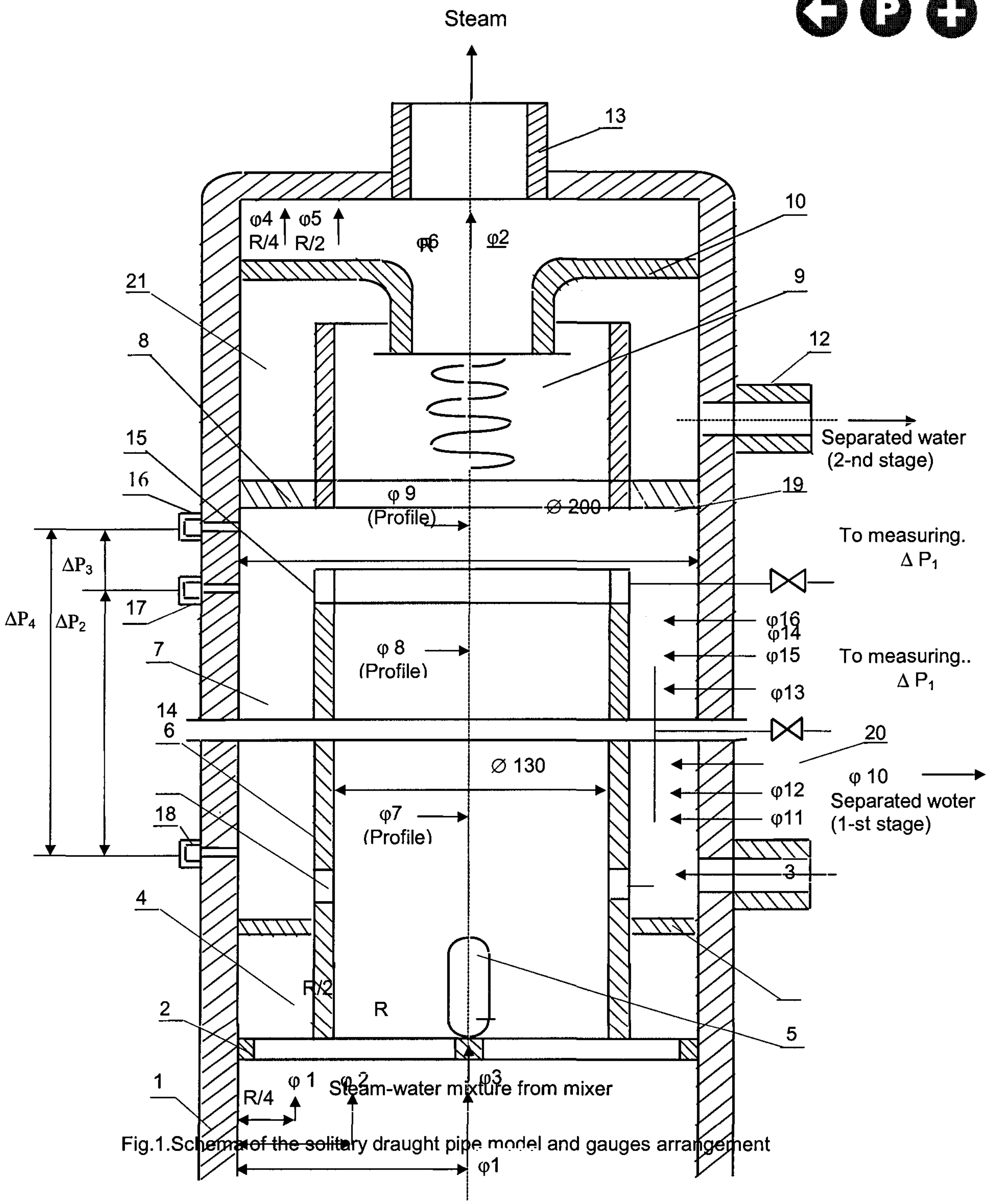
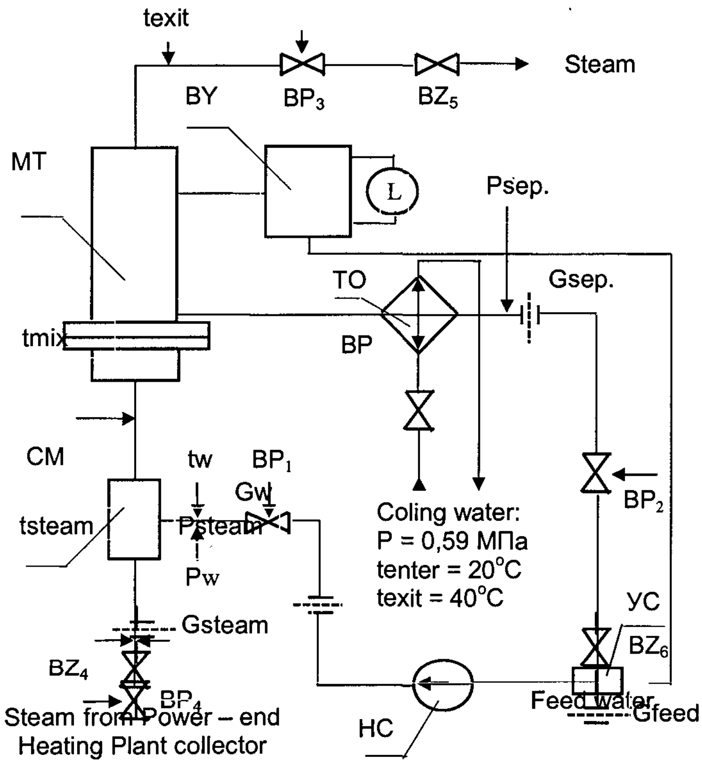


Fig.1.Schema of the solitary draught pipe model and gauges arrangement

Having passed through the draught pipe 6, steam-water mixture hits to the separating chamber 19 where it is separated partially; and separated water, as more heavy phase, is lowered in inter-pipe space (annulus) 7, and leaves test section through a branch pipe 20. The rest steam-water mixture moves in axial separator; steam through dissector 10 flows in steam volume and leaves the test section through a branch pipe 13. Separated water flows in inter-pipe space 21 and abandons test section through a branch pipe 12. During experiments the water level on submerged leaf 8 was supported of 200 ÷ 300 mm (height of axial separator was of ≈ 600 mm).
Thus, the components of the test section from the output lattice of the core 2 up to submerged leaf 8 are the same or very close constructively to the natural ones and are equal in height. In this part the test section is a full-scale one-pipe (as far as draught pipe is concerned) model of NPP with VK-300.
The output part of the test section (from submerged leaf 8 up to branch pipe 13) at the given stage of the work is carried out inadequately to nature.

TTP FACILITY
The principal hydraulic scheme of the TTP facility is presented in Fig. 2. It consists of the water circuit and steam pipelines.



Position	Name	K -ti
MT	One – tub model	1
BY	Level –meter tank	1
CM	Mixer	1
HC	Circular pump	1
TO	Heat exchanger	1
BP	Adjusting valve	4
BZ	Closing valve	3
G	Flow - meter	2
P	Manometer	3
УC	Mixing unit	

Fig.2. Hydraulic scheme of the TTP facility

Water from circulating pump NC through the flow-meter Gw and adjustable valve BP1 flows to the mixer CM. Together with water, steam at pressure of 3.2 ÷ 3.4 MPa and temperature of 400 ÷ 420 °C through closing valve BZ4 (located on the tap of the plant steam collector), flow-meter Gs, and adjustable valve BP4 flows to the mixer, as well.
Steam-water mixture formed in the mixer flows to the test section MO. Water separated on the draught pipe and mixing chamber flows, at the saturation temperature, to the circulating pump input through a branch pipe 20 acts, heat-exchanger TO, flow-meter Gsep, adjustable valve BP2, and mixing unit CY.
Water separated in axial separators through a branch pipe 12 and measuring tank MT flows to the mixing unit CY where it is mixed with water separated at the first step of separation, and flows further to the circulating pump input.

Separated steam through a branch pipe 13, adjustable valve BP3, and closing valve BZ5 is ejected to the atmosphere or flows to the heat-electric plant customers. It should be noted that water line: annulus, branch pipe 20, heat-exchanger TO and so on up to the mixing unit is a model of down-coming section of NPP down to the first step of separation.
Water line: branch pipe 12, measuring tank, etc. up to mixing unit is a model of down-coming section of NPP down to the second step of separation.
Thus, TTH facility is the closed circuit for water and unclosed for steam.

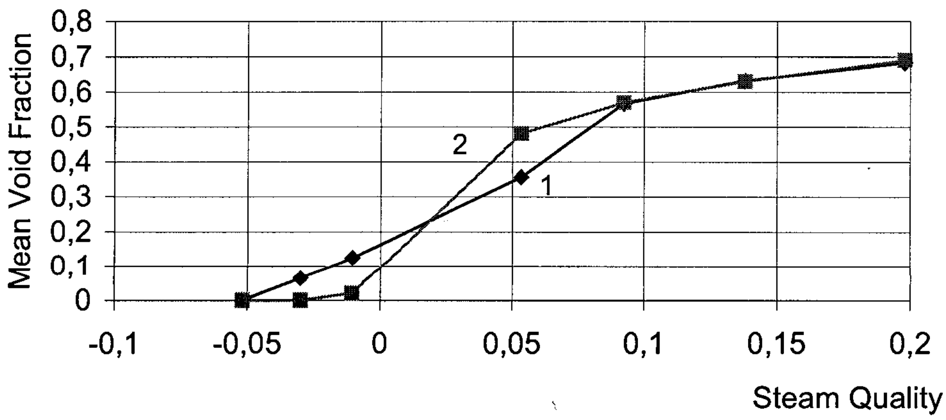
EXPERIMENTAL PROCEDURE

The experimental procedure was as follows:

- ensuring the circulation of steam-water mixture with required flow-rate and steam quality through the test section at pressure of 3.3 ÷ 3.4 MPa;
- measuring the thermal-hydraulic parameters at the specific, representing practical interest, up-coming and down-coming section of the circuit.

RESULTS OF EXPERIMENTS

The dependence of mean cross-sectional void fraction upon the steam quality on the draught pipe input is shown in Fig. 3. The results obtained allow some conclusions about void fraction in the channel of investigated geometry to be made. In this figure, except for experimental data, the curve $\varphi_{1m} = f(x)$, predicted by the code RELAP, is presented as well. In the region of equilibrium steam-water flow ($x \geq$ 0.10) the experimental and predicted values of void fraction are in agreement. In the field of non-equilibrium steam-water flow the agreement is not such good. However, as a whole, the discrepancy between predicted and experimental data can be recognized as satisfactory one.
One of major parameters of the circuit with free circulation are the pressure drops on different sections of the circuit. The obtained data of total pressure drops are used for verification of the codes (TRAC, RELAP, and ROSA), used for predictions of thermal-hydraulic performances of reactor facility VK-300.
In Fig. 4, the degree of steam-water mixture separation in the separation chamber against steam quality in the draught pipe input is presented. This plot has brightly expressed maximum in the region of x = 0.1 ÷ 0.11, being equal K_{sep} = 0.4, at nominal flow-rate of steam-water mixture through the draught pipe.



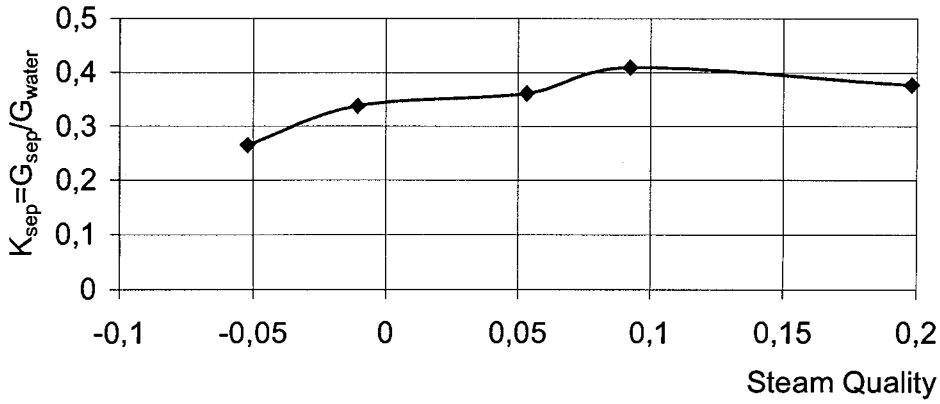
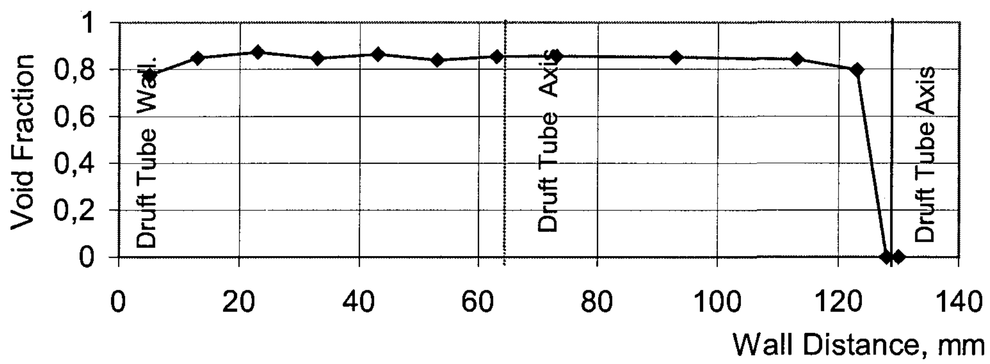


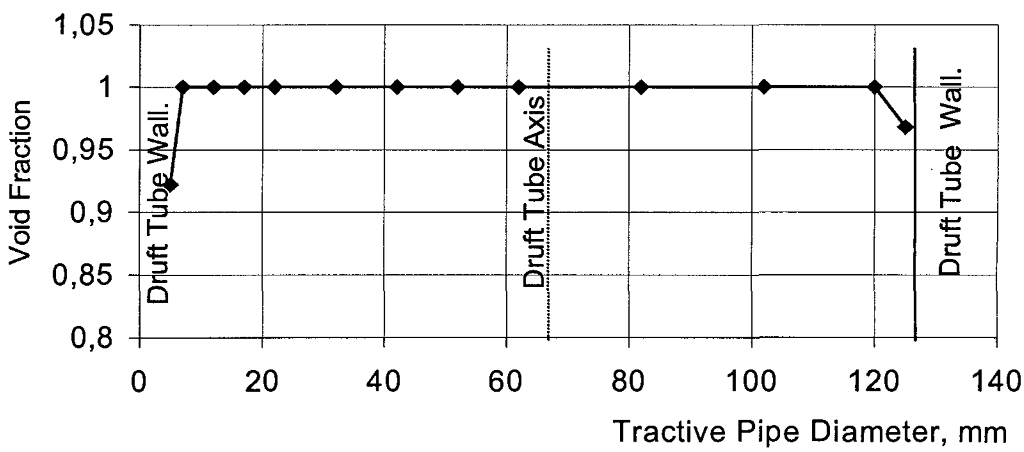
Fig.4. Dependence of Separation Degree in Separation Chamber upon Steam Quality in the Tractive Pipe Inlet at G_{min}=9kg/s.

In Figs. 5 and 6, the results of measuring of void fraction distribution over the draught pipe cross-section are shown at G_{mix} = 10 kg/s and steam quality on the draught pipe input x = 0.00 and x = 0.12, correspondingly. Some specific features of the results obtained should be noted.

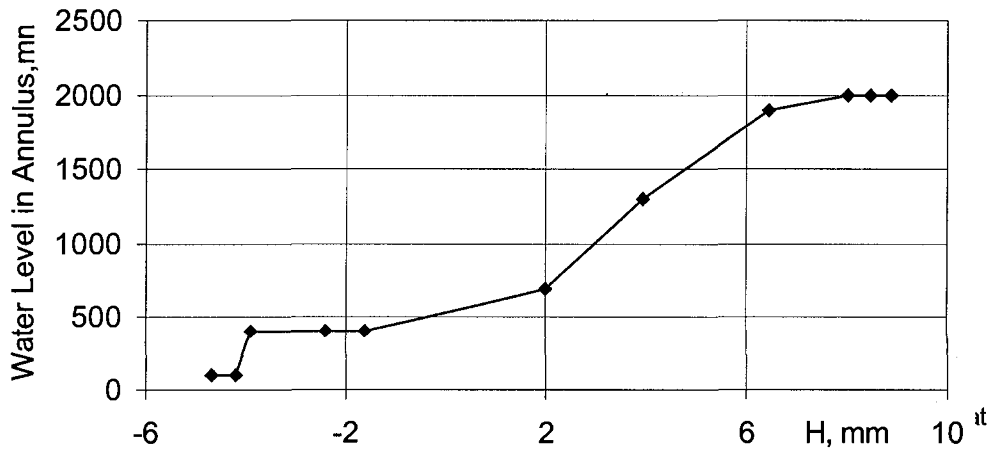
Already at values of steam quality on the mixer (core) exit close to zero the annular-dispersed flow regime of two-phase mixture in the draught pipe is observed. The liquid phase flows as a thin (about 5 mm in thickness) film on pipe wall; steam with water droplets dispersed in it occupies remaining cross-section of the draught pipe. At x = 0.12, the moisture in the flow core is absent, and the annular flow regime of steam-water mixture is formed.

The value of void fraction, averaged over the draught pipe cross-section φ_{avr}, at x = 0.00, is of 0.72, while its measured value at the draught pipe input is of 0.20. The calculation by the procedure of Z. L. Miropol'sky [5], supposing non-equilibrium of steam-water flow gives the value of mean φ in the draught pipe of 0.71, and that in mixing chamber of 0.53. Obviously, the agreement between experimental and predicted data in the draught pipe is rather good, and not quite satisfactory agreement in mixing chamber (φ_{exp} = 0.20, φ_{calc} = 0.53) can be explained by some incorrectness of the account of flow non-equilibrium at calculation.





At x = 0.12, in conditions of steam-water flow equilibrium, the agreement between experimental and predicted data is good. The measured values of mean void fraction in mixing chamber and draught pipe are of 0.53 and 0.88 and calculated – 0.59 and 0.81, correspondingly.
A special experiment was devoted to investigation of void fraction in annulus (transducers $\varphi_{10} \div \varphi_{16}$. As it was mentioned above, the working elements of the transducers were arranged along on a vertical generatrix of slot (breadth of the slot was of 30 мм). Transducer φ_{10} was placed practically at the annulus output (see branch pipe 20, Fig. 1), transducer φ_{16} – 100 millimeters lower than the draught pipe edge, and remaining transducers $\varphi_9 \div \varphi_{15}$ – on equal distances from each other along the annulus height.
The measurings were carried out, as follows. After initial flow regime, close to the natural one (G_{mix} = 9 kg/s, x = 0.10), being reached, by discrete unclosing the valve BZ2 (Fig. 2), the change (decrease) of hydraulic resistance of down-coming part of free convection circuit was modeled in the section relating to the first step of steam-water mixture separation. The results are shown in Fig. 7 in coordinates: "height of water level in annulus" versus "total pressure losses on the corresponding section of the circuit". The level of water in the annulus was obtained by measuring void fraction over the annulus height. It follows from Fig. 7, that in nominal regimes ($G_{mix} \approx$ 10 kg/s, x_{in} = 0.10 ÷ 0,12), the valve BP2 being closed as much as possible (maximum of hydraulic resistance), the annulus is entirely filled with water. In accordance with unclosing the valve BP2 and, hence, decrease of hydraulic resistance, the level of water in the annulus decreased up to the zero value.
The analysis of the plot in Fig. 7 confirms an opportunity of capture of steam by water separated in the separation chamber and its hitting to the core input.
So, in principle, if the choice of the hydraulic resistance of down-coming section of this part circuit is incorrect, termination of flow-rate and steam-water separation (too high hydraulic resistance ΔP_i), from one hand, and hit of steam to the core input (too low ΔP_i), from the other hand, are possible. From our point of view, this problem should be devoted the special experimental study on the modeling facility TTU.



CONCLUSIONS
During carrying out of this work a series of thermal-hydraulic performances of VK-300 reactor was investigated on model of solitary draught pipe for some elements of circuit with free convection.
The series the constructive solutions ensuring operation ability of reactor facility is confirmed, together with notions about thermal-hydraulic performances of the circuit with free convection, used for calculations of reactor facility by different codes.
In particular, it is shown, that in all studied range of steam quality, either annular-dispersed or dispersed flow regimes of steam-water mixture exists in draught pipe. It results in the essential separation of steam-water mixture at the crimp of draught pipes ($K_{sep} \cong$ 0.4). For the separation coefficient on the draught pipes to be increased at such structure of the flow, it is useful to make draught pipes perforated in

their upper section. It will increase separation coefficient at the first step and will create more favorable separation conditions at the second step (axial separators), including decrease of pressure losses.
The measured values of void fraction in mixing chamber and draught pipe are satisfactorily agree with predicted by procedure of Z. L. Miropol'sky [5] and by the code RELAP and can be used for verification of prediction codes used for calculation of thermal-hydraulics of VK-300 facility.
It is shown, the hit of steam into the annulus simulating inter-pipe space and to the core input is possible. Height of steam hovering at this section of the circuit depends upon its hydraulic resistance

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