THE QUESTIONS OF LIQUID METAL TWO-PHASE FLOW MODELLING IN THE FBR CORE CHANNELS

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Abstract

The two-fluid model representation for calculations of two-phase flow characteristics in the FBR fuel pin bundles with liquid metal cooling is presented and analysed. Two conservation equations systems of the mass, momentum and energy have been written for each phase. Components accounted the mass-, momentum- and heat transfer throughout the interface occur in the macro-field equations after the averaging procedure realisation. The pattern map and correlations for two-fluid model in vertical liquid metal flows are presented. The description of processes interphase mass- and heat exchange and interphase friction is determined by the two-phase flow regime. The opportunity of the liquid metal two-phase flow regime definition is analysed.

1. INTRODUCTION

The nuclear reactor heat removal with natural circulation origin in the reactor first contour, with coolant boiling, with consequent possible dryout in the core (the crisis of heat exchange), is one of the most unexplored and hardly predictable modes of the NPS accident situations. Now there is a rather large number of the machine codes for the analysis of similar processes for reactors with the cooling by water. The problem of modelling the non-stationary thermohydraulic processes in the fast reactor first contour in which the liquid metal is used as the coolant is in a more complicated position.

This paper is devoted to description of a two-fluid mathematical model of the heat exchange process in the fast reactor circulating contour under heat removal conditions. The presented system of constitutive relations is basically constructed on empirical relations and essentially depends on a two-phase flow regime. However adequate description of the boundaries between liquid metal two-phase flow regimes is hampered. That reduces to a problem of a experimental pattern maps creation which could be used in computer codes for calculation the non-stationary processes in the fast reactor first contour.

2. THE STATEMENT FOR A MODEL

The necessary assumptions for simplification of full statement for a model could be defined as follows:

(1) The phases pressure is equal.
(2) Phases velocities on the interface are equal.
(3) The force of joined masses is zero.
(4) The through passage section area function is continious.

With allowance for these assumptions the two-phase flow model will be named as a two-fluid model of unequal phases velocities and temperatures.

The conservation equations system has the following aspect:

$$\begin{cases} \frac{\partial}{\partial\tau}(\varphi_k\rho_k\omega)+\frac{\partial}{\partial z}(\varphi_k\rho_k w_k\omega)=\Gamma_{lk}\omega \\ \frac{\partial}{\partial\tau}(\varphi_k\rho_k w_k\omega)+\frac{\partial}{\partial z}(\varphi_k\rho_k w_k^2\omega)=\Gamma_{lk}w_l\omega-\varphi_k\omega\frac{\partial p}{\partial z}-s_{wk}\tau_{wk}\omega+s_l\tau_{lk}\omega \\ \frac{\partial}{\partial\tau}(\varphi_k\rho_k h_k\omega)+\frac{\partial}{\partial z}(\varphi_k\rho_k h_k w_k\omega)=\Gamma_{lk}h_l\omega+\varphi_k\omega\frac{\partial p}{\partial\tau}+w_k\varphi_k\omega\frac{\partial p}{\partial z}+ \\ \qquad +(w_k-w_l)p\omega\frac{\partial\varphi_k}{\partial z}+s_{wk}q_{wk}\omega+s_l q_{lk}\omega \end{cases} \tag{1}$$

$k = l, g.$

The conservation equations on the interface can be noted as follows:

$$\begin{cases} \sum_{k=l,g}\Gamma_k=0 \\ \sum_{k=l,g}(\Gamma_k w_{lk}-\tau_{lk})=0 \\ \sum_{k=l,g}(\Gamma_k h_{lk}+q_{lk}-\tau_{lk}w_{lk})=0 \end{cases} \tag{2}$$

The system of six differential equations includes six unknowns: h_l, h_g, w_l, w_g, φ, p. The model is made for calculation of processes in a contour with natural circulation. Therefore mathematically propulsion can be found through a residual of contour segments weights. Thus, the pressure falls out of an unknown variables list and the initial conservation equations system undergoes the following modifications:

$$\begin{cases} \frac{\partial\rho_m}{\partial\tau}+\frac{\partial}{\partial z}(\rho_m w'_m)=0 \\ \frac{\partial}{\partial\tau}(\varphi_g\rho_g\omega)+\frac{\partial}{\partial z}(\varphi_g\rho_g w_g\omega)=\Gamma_{lg}\omega \\ \frac{\partial}{\partial\tau}(\varphi_k\rho_k w_k\omega)+\frac{\partial}{\partial z}(\varphi_k\rho_k w_k^2\omega)=\Gamma_{lk}w_l\omega-\varphi_k\omega\frac{\partial p}{\partial z}-s_{wk}\tau_{wk}\omega+s_l\tau_{lk}\omega \\ \frac{\partial}{\partial\tau}(\varphi_k\rho_k h_k\omega)+\frac{\partial}{\partial z}(\varphi_k\rho_k h_k w_k\omega)=\Gamma_{lk}h_l\omega+\varphi_k\omega\frac{\partial p}{\partial\tau}+w_k\varphi_k\omega\frac{\partial p}{\partial z}+ \\ \qquad +(w_k-w_l)p\omega\frac{\partial\varphi_k}{\partial z}+s_{wk}q_{wk}\omega+s_l q_{lk}\omega \end{cases} \tag{3}$$

That is, the momentum and energy conservation equations for each phase and mass equation for gas remain without modifications and instead of the mass equation for fluid the mass equation for a two-phase mixture is decided. In an outcome to a list from five unknowns sixth is added (w'_m): it is possible to describe as a two-phase mixture velocity modification owing to that the volumetric extension. It is obvious that in difference from the momentum conservation equations, in which the velocity of each phase is concerning the contour length, the value w'_m is of the rather pseudo-fixed coolant.

So, we have a system of six differential equations with six unknowns: h_l, h_g, w_l, w_g, φ, w'_m. We have a list of parameters derivatives from these unknowns: ρ_l, ρ_g, t_l, t_g, which are connected by the following relations:

$$t_k = {}^{h_k}\!/_{C_{pk}}; \tag{4}$$

$$\rho_k = \rho_{0k} - \beta_k \cdot t_k, \tag{5}$$

and also series of auxiliary magnitudes:

S_I – the interface boundary length;
w_I – the interface rate;
$\tilde{A}_{Il}$, $\tilde{A}_{Ig}$ – the mass exchange velocity on the interface;
τ_{Il}, τ_{Ig} – interphase shear stress of phases;
τ_{wl}, τ_{wg} – wall shear stress of phases;
q_{Il}, q_{Ig} – interphase heat flux;
q_{wl}, q_{wg} – wall heat flux.

2.1. Interface boundary length

The interface boundary length is directly through magnitude of the interphase area:

$$s_I = a_I \cdot \omega, \tag{6}$$

The analysis of calculation techniques data is submitted in [1].

The interphase area depends on a coolant flow pattern as follows:

Nucleate regime [2]:

$$a_I = \frac{3\varphi}{r_p} \tag{7}$$

where $r_p = 0.06147 \cdot \dfrac{We_{кр}}{(2\rho_m w_R)^2}$ – Characteristic size of bubbles;

$We_{êð} = 1.24$,

$w_R = w_g - w_l$.

Beam and turbulence regime [3]:

$$a_I = \frac{4.5}{d_\Gamma} \cdot \frac{\varphi - \varphi_{gs}}{1 - \varphi_{gs}} + \frac{3\varphi_{gs}}{r_p} \cdot \frac{1 - \varphi}{1 - \varphi_{gs}} \tag{8}$$

where φ_{gs} – Average steam fraction on a liquid fuse segment.

Annular and disperse-annular regime [3]:

$$a_I = \frac{4\xi_ш}{d_\Gamma} \cdot \sqrt{\frac{\varphi}{1 - \varphi_{ld}}} + \frac{3\varphi_{ld}}{r_p} \cdot \frac{\varphi}{1 - \varphi_{ld}} \tag{9}$$

where φ_{ld} – volumetric drops concentration in the steam kernel;

$\xi_ø$ – the grain parameter.

$$\varphi_{ld} = \frac{E^*(1 - \varphi)}{\varphi} \tag{10}$$

$$E^* = \frac{1}{1 - \left(1 - \dfrac{1}{E}\right)\dfrac{w_d}{w_l}} \text{ – volumetric drops concentration} \tag{11}$$

$$E = 1 - exp\left[-0.23\left(w_g - w_E\right)\right] \text{ – drops fraction} \tag{12}$$

$$w_E = 2.3\left[13\sigma \cdot \left(\frac{\rho_l - \rho_g}{\rho_g^2}\right)\right]^{0.25} \text{ – the drops ablation velocity} \tag{13}$$

Disperse regime [2]:

$$a_I = \frac{3(1-\varphi)}{r_p} \tag{14}$$

where $r_p = 0.06147 \cdot \frac{13 \cdot \sigma}{(2\rho_m w_R)^2}$

2.2. Interface velocity

The interface velocity is generally determined by the friction forces balance equation in couples vapour – interface and fluid – interface:

$$\xi_{Ig}\rho_g(w_g - w_I)^2 - \xi_{Il}\rho_l(w_l - w_I)^2 = 0 \tag{15}$$

Which solution has the following aspect:

$$w_I = \frac{\left(\xi_{Ig}\rho_g w_g - \xi_{Il}\rho_l w_l\right) - \sqrt{\xi_{Ig}\rho_g \xi_{Il}\rho_l \left(w_g - w_l\right)}}{\xi_{Ig}\rho_g - \xi_{Il}\rho_l} \tag{16}$$

As reasonable simplification it is possible to suppose that $\xi_{Ig}\rho_g = \xi_{Il}\rho_l$. Then the interface velocity is equal:

$$w_I = \frac{w_g - w_l}{2} \tag{17}$$

2.3. Interface mass exchange

There are some various groups of constitutive relations intended for an evaluation of a mass flow through the interface used at a two-fluid models creation for known thermohydraulic codes:

RELAP5/MODL [4]

In a model the empirical relation for steam phase generation intensity in all range of steam fraction is used:

$$\Gamma_g = \frac{-6.45 \cdot 10^{-3}\left[(\rho w)_m + (\rho w)_0\right]^2 \sqrt{p}}{\rho_g}\left(x + 10^{-5}\right)(x - \tilde{x}) \tag{18}$$

where $\tilde{x} = \frac{h_{in} - h_l}{r} + \frac{q\pi z}{\omega r}$ – quality;

$(\rho w)_0 = 3500\ kg/(m^2 s)$.

SABENA [5]

$$\tilde{A}_g = -\tilde{A}_l = \tilde{A}_e + \tilde{A}_c \tag{19}$$

where $\frac{p_s}{\sqrt{t_l}} - \frac{p}{\sqrt{t_g}} > 0$

$$\Gamma_e = \lambda_e a_I \varphi_g \varphi_l \left(\frac{M}{2\pi R}\right)^{1/2} \cdot \left(\frac{p_s(t_l)}{\sqrt{t_l}} - \frac{p}{\sqrt{t_g}}\right) \text{è } \tilde{A}_c = 0 \tag{20}$$

in case $\frac{p_s}{\sqrt{t_l}} - \frac{p}{\sqrt{t_g}} \le 0$

$$\Gamma_c = \lambda_c a_I \varphi_g \varphi_l \left(\frac{M}{2\pi R}\right)^{1/2} \cdot \left(\frac{p_s(t_l)}{\sqrt{t_l}} - \frac{p}{\sqrt{t_g}}\right) \text{è } \tilde{A}_e = 0 \tag{21}$$

where $\lambda_{\tilde{n}}$ è λ_e – condensation and evaporation coefficients accordingly.

THERMIT [6]

With allowance for relation (20):

$$\Gamma_e = a_l \begin{cases} 0, \ in \ \ case \ \ T_l \le T_d \\ q_w \dfrac{T_l - T_d}{T_s - T_d}, \ in \ \ case \ \ T_d < T_l < T_s \\ q_w, \ in \ \ case \ \ T_l \ge T_s \end{cases} \tag{22}$$

$$\Gamma_c = a_l \frac{k_l}{0.015 r_b}(t_l - t_w) \tag{23}$$

Where a bubble temperature t_d is calculated by relation:

$$T_s - T_d = \frac{q_w}{\alpha}, \ \alpha = 2.44 \frac{\lambda}{d_\Gamma}\left(\frac{G d_\Gamma}{\mu}\right)^{1/3} Pr^{1/3}\left(\frac{h_{in}}{h_l}\right)^{1/3}\left(\frac{r}{h_l}\right)^{1/3}$$

There is very simple in a programming context formula for calculation of a mass exchange velocity on the interface [2]:

$$\Gamma_k = \left[(-1)^n \sum_{k=l,g} \alpha_{lk}(t_s - t_k)/r\right] \cdot \frac{s_l}{\omega} \tag{24}$$

where $n = 1$, *in case* $k = g$;
$n = 2$, *in case* $k = l$.

From a mass conservation equation on the interface follows:
$\tilde{A}_{ll} = -\tilde{A}_{lg}$ è $\tilde{A}_l = |\tilde{A}_{lg}|$.

2.4. Interface friction.

The interphase shear stress can be calculated by relation:

$$\tau_{lk} = \xi_{lk} \frac{\rho_k}{2}(w_k - w_l)^2 \tag{25}$$

The interface rate is determined under the formula (17). With allowance for it we have:

$$\tau_{lk} = \xi_l \frac{\rho_k}{8}(w_g - w_l)|w_g - w_l| \tag{26}$$

where ξ_l – the interface friction coefficient which depends on a coolant flow pattern and can be calculated by following relations.

Nucleate regime [7]:

$$\xi_l = \frac{24}{Re} + \frac{4}{\sqrt{Re}} + 0.4 \tag{27}$$

where $Re = \dfrac{2 r_p \rho_c (w_g - w_l)}{\mu_c}$

Slug regime [3]:

$$\xi_l = 9.8(1 - \varphi)^3. \tag{28}$$

Turbulence regime [3]:

$$\xi_l = 0.375(1-\varphi)^2 . \tag{29}$$

Annular regime [4]:

$$\xi_l = \begin{cases} \dfrac{64}{Re_{gl}}, \ in \ \ case \ \ Re_{gl} < 500 \\ \dfrac{64}{Re_{gl}}\left(\dfrac{1500 - Re_{gl}}{1000}\right) + \dfrac{Re_{gl} - 500}{1000} x^{\gamma} \ \ in \ \ case \ \ 500 < Re_{gl} < 1500 \\ 0.02\left[1 + 150\left(1 - \sqrt{\varphi}\right)\right] \ \ in \ \ case \ \ Re_{gl} > 1500 \end{cases} \tag{30}$$

where $Re_{gl} = \dfrac{2\rho_g \, Re\left(w_g - w_l\right)}{\mu_c}$;

$$Re = \sqrt{\varphi}\,\frac{d_\Gamma}{2} ; \quad \gamma = 0.02\left[1 + 150\left(1 - \sqrt{\varphi}\right)\right]$$

Disperse regime [8]:

$$\xi_l = \left(\frac{24}{Re} + \frac{4}{\sqrt{Re}} + 0.4\right) K_\varphi K_{wl} K_{Ma} \tag{31}$$

where $K_\varphi = (1-\varphi)^{-2.7}$ – influence of a disperse phase concentration;

$K_{wl} = exp\left(0.03We_p^{1.5}\right)$ – influence of a dispersible particles strain;

$K_{Ma} = 1 + exp\left(-\dfrac{0.427}{Ma_c^{4.63}} - \dfrac{3}{Re_c^{0.88}}\right)$ – influence of a carrying phase compressibility;

$Ìa_ñ$ – the Makh Number of a carrying phase.

2.5. Wall shear stress of phases.

Generally total two-phase flow friction force on a wall is determined by a relation:

$$\tau_w s_w = \sum_{k=l,g} \tau_{wk} s_{wk} \tag{32}$$

and $\tau_{wk} = \xi_{wk} \dfrac{\rho_k w_k^2}{8}$

where s_{wk} – wall surface which is in contact with the phase k and relayted to a unit of flow volume.

$$s_{wk} = \frac{4\varphi_k}{D} \ (D - \text{an equivalent pipe diameter}). \tag{33}$$

The friction description for each phase on channel wall assumes evaluation of a total two-phase flow friction force on a wall and consequent separation of this force on component concerning to separate phases. Mechanical interaction of two-phase flow phases with channel walls is investigated very poorly and requires to accept some assumptions. As such an assumption it can be considered, that the vapour friction on a wall in nucleate, slug and disperse-annular regimes is equal to zero. Then the liquid phase friction on a wall is calculated by relations for a total friction force.

Pin bundles [9]:

$$\tau_w = \xi_w \frac{\rho_l w_0^2}{2d_\Gamma}, \tag{34}$$

where

$$\xi_w = \xi'_{wl}\,\psi\left[1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right];$$

$$\psi = \left[1 + 0.57\left(\frac{1}{0.2 + k} - 5.2(s/d)^2\right)\cdot(s/d)^{0.125}\cdot\left(1 - (s/d)^2\right)\right]\cdot\left[1 + x\left(\frac{\mu_l}{\mu_g} - 1\right)\right]^{-0.2\,s/d};$$

$$k = \frac{w_0}{\sqrt{g d_\Gamma}}\frac{\rho_g}{\rho_l};$$

$w_0 = \dfrac{\rho w}{\rho_l}$ – circulating velocity;

ξ'_{wl} – the hydraulic resistance coefficient in a bundle for a single-phase flow.

The method of the two-phase flow friction definition on a wall by two-phase factor [2] is very much widespread also:

$$\tau_w = \tau'_l \cdot \Phi_l^2; \tag{35}$$

where τ'_l – wall shear stress of an initial single-phase fluid flow;

$\Phi_l^2 = 1 + \dfrac{20}{X} + \dfrac{1}{X^2}$ – two-phase factor;

X – The Martinelly-Lockart parameter which in case of turbulence flow of both fluid and gas can be found by the Blasius law:

$$X^2 = \left(\frac{\mu_l}{\mu_g}\right)^{0.25}\left(\frac{1-x}{x}\right)^{1.75}\frac{\rho_g}{\rho_l}.$$

Another path of approximate exposition of separate phases friction forces on a wall consists of reformulating the problem to appropriate phase flow in some equivalent pipe. In this case the two-phase flow regime is essential.

Disperse regime (nucleate, disperse-drop):

$Re_{ek} = \dfrac{\rho_k |w_k| D}{\mu_k}$ – Reynolds Number for phase flows in equivalent pipes;

$$\xi^L_{wk} = \frac{64}{Re_{ek}} \text{ in case } 1 < Re_{ek} < 2000 \text{ [4]}; \tag{36}$$

$$\frac{1}{\sqrt{\xi^T_{wk}}} = 1.74 - 2\lg\left[\frac{2\varepsilon}{D} + \frac{18.7}{Re_{ek}\sqrt{\xi^T_{wk}}}\right] \text{ in case } Re_{ek} > 4000 \text{ [4]}. \tag{37}$$

In case $2000 < Re_{ek} < 4000$ the friction coefficient can be determined by the linear interpolation on variable $1 / Re_{ek}$ as follows:

$$\xi_{wk} = \left(2 - \frac{4000}{Re_{ek}}\right)\left(\xi^T_{wk} - \xi^L_{wk}\right) + \xi^L_{wk}. \tag{38}$$

Annular regime (slug, annular, disperse-annular):

The area of vapour phase contact with a wall is equal to zero. The Reynolds Number of an equivalent flow only for a liquid phase accordingly is:

$$Re_{el} = \frac{(1-\varphi)\rho_l |w_l| D}{\mu_l};$$

And the calculation of friction factors is calculated by the equations (36) - (38).

2.6. Interface heat exchange.

The heat exchange intensity between phases and interface is characterised by interface heat exchange factors:

$$q_{Ik} = \alpha_{Ik} \cdot (t_I - t_k) \tag{39}$$

where it is possible to consider the interface temperature to be equal to the temperature of saturation ($t_I = t_s$).

The relations for the definition of interface heat exchange factor essentially depend on a two-phase flow pattern. Their analysis is submitted in [10].

Nucleate and slug regimes:

$$\alpha_{Ik} = \frac{Nu_{Ik}\lambda_k}{2r_p} \tag{40}$$

where for the liquid phase:

$$Nu_{II} = Nu_0 + 1.13Pe^2\left(\frac{1}{13Ja^{3.3} + Pe^{1.5}} - \frac{6Ja^{0.63}}{31Ja^{4.3} + Pe}\right);$$

$$Nu_0 = 3.9Ja\left[1 + 0.5\left(Ja \cdot \pi/6\right)^{2/3} + Ja \cdot \pi/6\right];$$

$$Nu_{II} = Pe\sqrt{\frac{4}{\pi}} \text{ in case } Ja << 1,\ Pe >> 1;$$

$$Nu_{II} = 2 + 2\varphi + 22.5\varphi^2 \text{ in case } Ja << 1,\ Pe << 1;$$

$$Pe = 2r_p\frac{|w_l - w_g|}{a_l};$$

$$Ja = \frac{1}{r}\frac{\rho_l}{\rho_g}C_{Pl} \cdot \left(t_l - t_g\right);$$

r_p – characteristic size of bubbles, of which calculation technique is reduced in item 1.
for the vapour phase $Nu_{Ig} = 16$.

Disperse-annular regime:

$$\alpha_{II} = \frac{Nu_{II}\lambda_l}{\delta_l} \tag{41}$$

where $Nu_{II} = 1$.

$$\alpha_{Ig} = \frac{Nu_{Ig}\lambda_g}{R - \delta_g} \tag{42}$$

where

$$Nu_{Ig} = \frac{0.023\,Re_g^{0.8}\,Pr_g^{0.4}}{4\delta_l/d_\Gamma}\sqrt{\xi_{Iш}\frac{4\delta_l/d_\Gamma}{\xi_I}};$$

$$Re_g = \rho_g|w_g - w_l|\frac{2(R - \delta_l)}{\mu_g};$$

$\xi_{Iø}$ – the interface grain parameter;
δ_l – the fluid film thickness.

2.7. Heat exchange of phases with walls.

The calculation of heat exchange of phases with channel walls is produced by analogy to above mentioned calculation of friction forces that is the summarised heat flow between a wall and coolant is determined and then the distribution of a common flow between phases is:

$$q_w s_w = \sum_{k=l,g} q_{wk} s_{wk} \; ; \tag{43}$$

$$q_w = \alpha_w \cdot (t_w - t_l);$$

$$q_{wk} = \alpha_{wk} \cdot (t_w - t_k).$$

For calculation of the heat transfer coefficient from a wall to a two-phase mixture the following formula [9] can be used:

$$Nu = 0.017\, Re_{cм}^{0.8}\, Pr_w^{0.8}\, Y \tag{44}$$

where:

$$Re_{cм} = \left(\frac{\rho w d}{\mu_g}\right)\left[1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right];$$

$$Y = 1 + 0.5\left(\frac{\rho_l}{\rho_g} - 1\right)^{0.8}(1 - x) \text{ in case } \frac{\rho_l}{\rho_g} < 450;$$

$$Y = 1 + 70(1 - x) \text{ in case } \frac{\rho_l}{\rho_g} > 450.$$

For the heat transfer to a vapour [11]:

$$Nu = 0.023\, Re_g^{0.8} \cdot Pr_g^{0.4}$$

2.8. Criteria of the two-phase flow regimes definition.

The calculation of some thermohydraulic characteristics such as length of the interface boundary, interface friction, interface heat exchange, friction of phases with walls is based on the two-phase flow regimes definition. The two-phase flow regimes definition depends on large number of parameters. Therefore, despite of rather large number of researches carried out, the problem of the two-phase flow regimes definition remains now appreciably unsolved. It is the only actual way to describe the boundaries between regimes with the help of approximate maps of pattern. The large number of parameters influencing to a flow regime and their complicated association from each other does not allow to construct a "universal" map of pattern and reduces in a population of pattern maps each of which describes a single class of two-phase flow.

For steam-water flows there is a series of maps used in calculations and empirically obtained relations for delimitation of two-phase flow regimes. In the contrary for a liquid metal two-phase flow there is no pattern map. Therefore it is necessary to investigate the following problem: whether the use of pattern maps obtained for water boiling in calculations of liquid metal two-phase flow characteristics is possible, or in view of the liquid metal boiling process specific feature the construction of a special pattern map is necessary?

As a basis at a construction the pattern map for calculation characteristics of vertical steam-water flows the Bennett pattern map is used [12]. The Bennett pattern map obtained for steam-water flows under high pressure conditions in vertical pipes and shown on fig. 1.

In [13] the pattern map for a vertical two-phase flow constructed on the basis of researches with the laser holography of steam-water flows structural performances is

presented. The pattern map was constructed under the following conditions: in a pipe by a diameter $d = 8.8\ mm$ at pressure $p = 1 \div 6.9\ MPa$, in an annular channel by a diameter $d = 5.5\ mm$ at pressure $p = 1 \div 9.8\ MPa$ (fig. 2).

There are also dimensionless relations for the regimes boundaries:

For the boundary between nucleate and slug regimes:

$$x = \pm 0.01; \tag{45}$$

For a upper bound of the slug regime:

$$x = (4.5 \pm 1.5) \cdot 10^{-2} \left(\frac{(\rho w)^2}{\rho_{ls}^2 g d_l} \right)^{-0.25}. \tag{46}$$

In spite of the fact that both Bennett pattern maps (fig. 1) and Doroschuk pattern map (fig. 2) are obtained for water boiling under similar conditions of high pressure, the comparison shows their essential difference (fig. 3). It once again proves the statement about a complicated association of a two-phase mixture flow regimes from various thermophysic and hydrodynamic parameters. Though, it is necessary to note, that the Bennett map was constructed in 1965 when the computing tools could not supply necessary accuracy at handling of an experimental material, and the Doroschuk map (1985) was constructed by using the advanced technological developments.

Therefore it is necessary to modificate initial maps with the purpose of a release from an association of some regimes from the most essential defining parameters.

The modification of maps can be carried out in two directions. The first from them: whenever possible it is less deviating from a pre-image to facilitate use of a map in calculated codes by the realisation of the following operations:

- The passage from coordinates (ρW, x) to coordinates (ρW, φ), that probably will allow with smaller errors to describe boundaries between regimes not depending on pressure;
- Simplification of the regimes boundaries representation by direct lines;
- The unity of all regimes at large values φ to an annular regime at which all the fluid is considered to be concentrated in a liquid film on the wall.

The outcome of similar modification of a Bennett map is presented in [14] and is shown on fig. 4. In a similar way it is possible to conduct modification of a Doroschuk map. The problem is that the experimental data used at its construction are obtained for large scale of pressure ($p = 1 \div 9.8\ MPa$). As corollary specified interval of pressure corresponds broad interval of steam density on saturation line which in turn is one of the basic magnitudes at the definition true volumetric steam fraction φ from quality x. Therefore as shown in fig. 5 in an outcome of Doroschuk map modification regimes boundaries are mapped for various pressure ambiguously.

The second direction of modification differs by more significantly simplification of a pattern map rebuilt in coordinates (ρW, φ) and introduction of transitional zones between regimes.

In a fig. 6 and fig. 7 the pattern maps obtained by this method from a Bennett map ([4, 15]) are shown. The slug regime can appreciably be treated as transitional from nucleate to disperse-annular regime (as for example in [15]). Therefore in this case the transitional zone between nucleate and slug regimes is not necessary.

The researches in the liquid metal flows regimes definition are not so rich in experimental and theoretical data. It is enough to say that a pattern map of liquid metal adopted for use in calculated codes similar Bennett map does not exist yet. From experimental

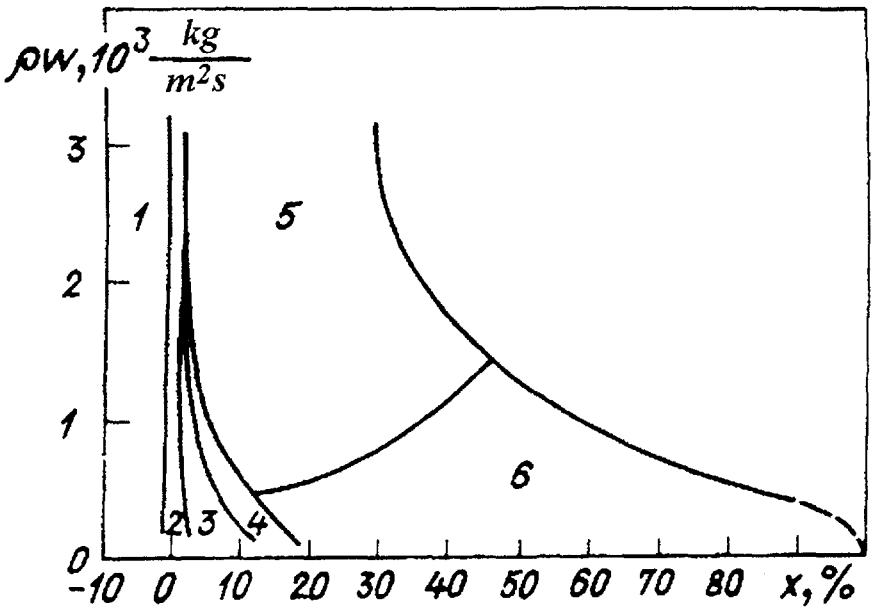

Fig. 1. Bennett pattern map. Regimes:
1 – single-phase flow, 2 – nucleate, 3 – slug, 4 – emulsion, 5– disperse-annular, 6 – annular.

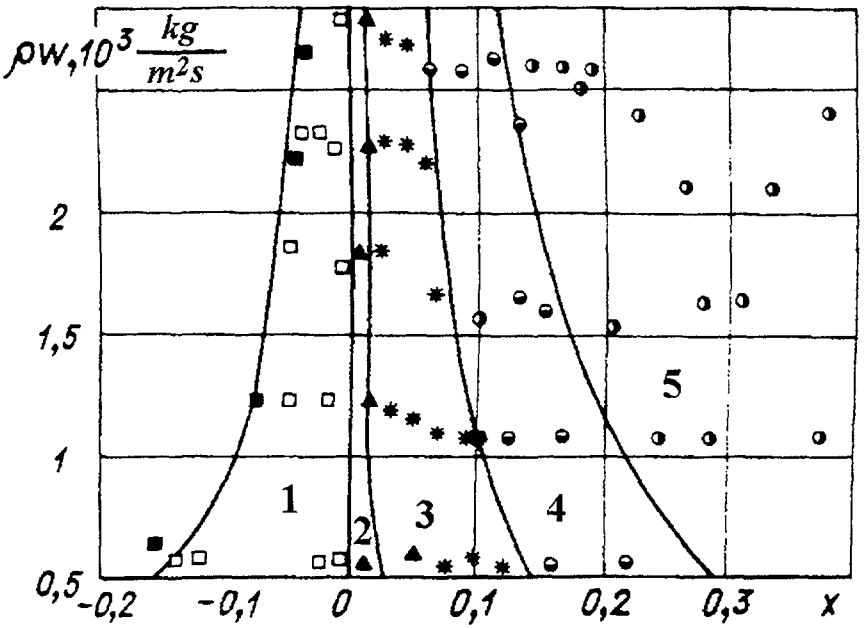

Fig. 2. Doroschuk pattern map. Regimes:
1 – nucleate, 2 – transitional zone, 3 – slug, 4, 5 – disperse-annular.

pattern maps obtained for liquid metal boiling it is possible to reduce a map presented in Yamaguchi paper [16] constructed for $\rho W < 250$ *kg/m²s* (fig. 8) and a map constructed in IPPE [17] for a large interval of parameters on the basis of experimental data on eutectic alloy sodium-potassium (22%-78%) boiling conditions in the fast reactor core under the natural circulation conditions at pressure 0.6 bars (fig. 9). The comparison between them has shown a good coincidence (fig. 10).

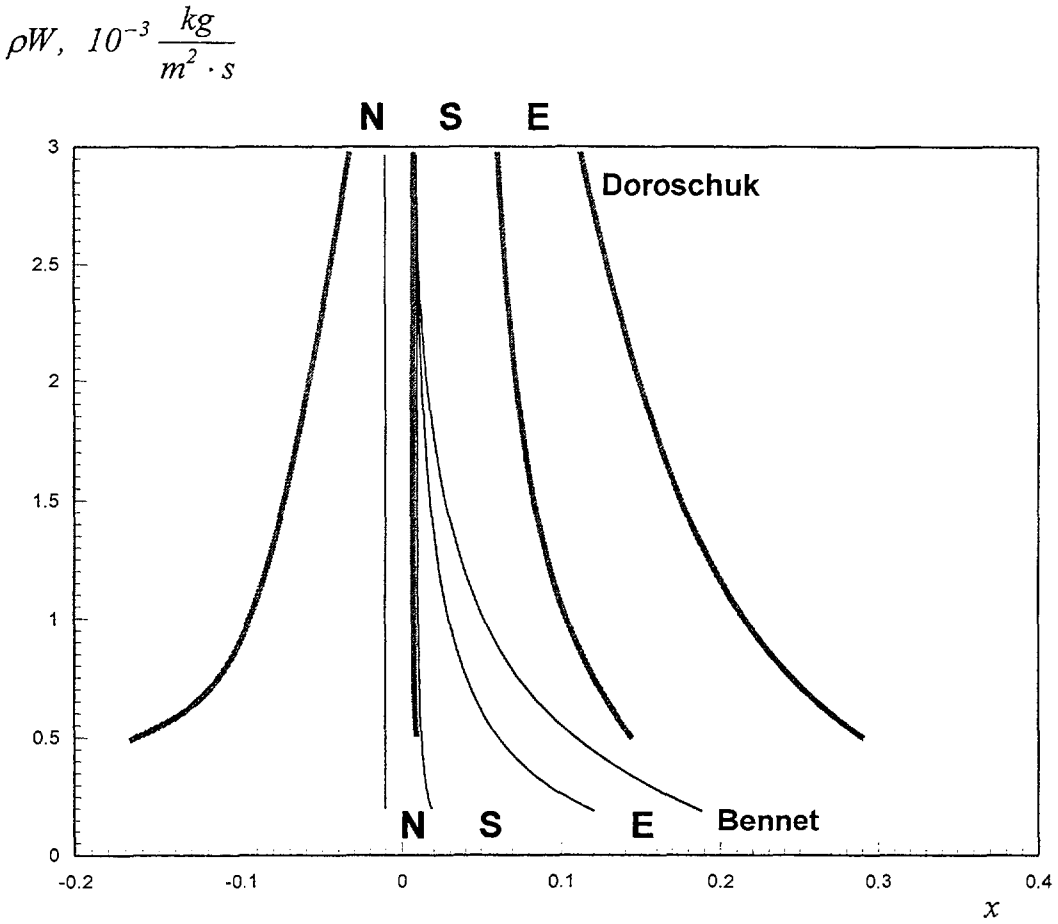

Fig. 3. The comparison of Bennett pattern map and Doroschuk pattern map.
N -- nucleate regime, S -- slug regime, E -- emulsion regime.

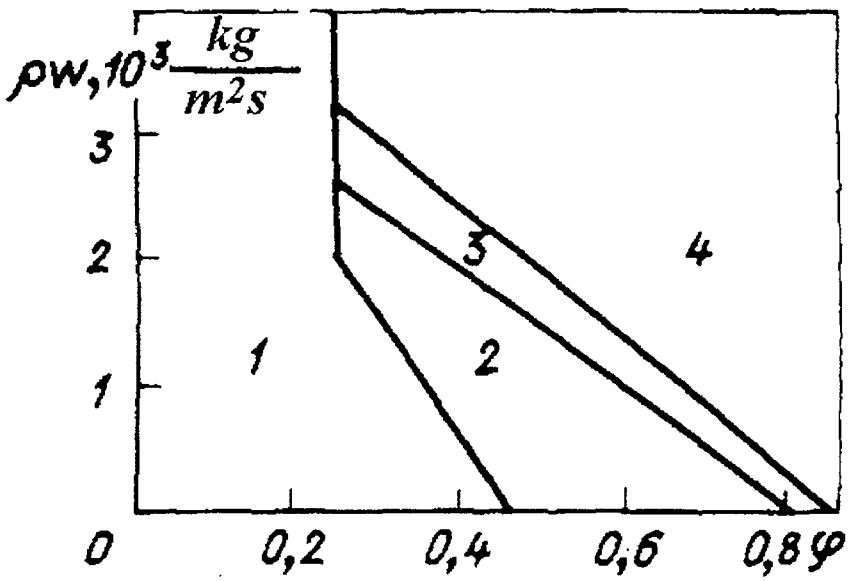

Fig. 4. The Bennett pattern map modified by the first method. Regimes:

1 – nucleate, 2 – slug, 3 – emulsion, 4 – annular.

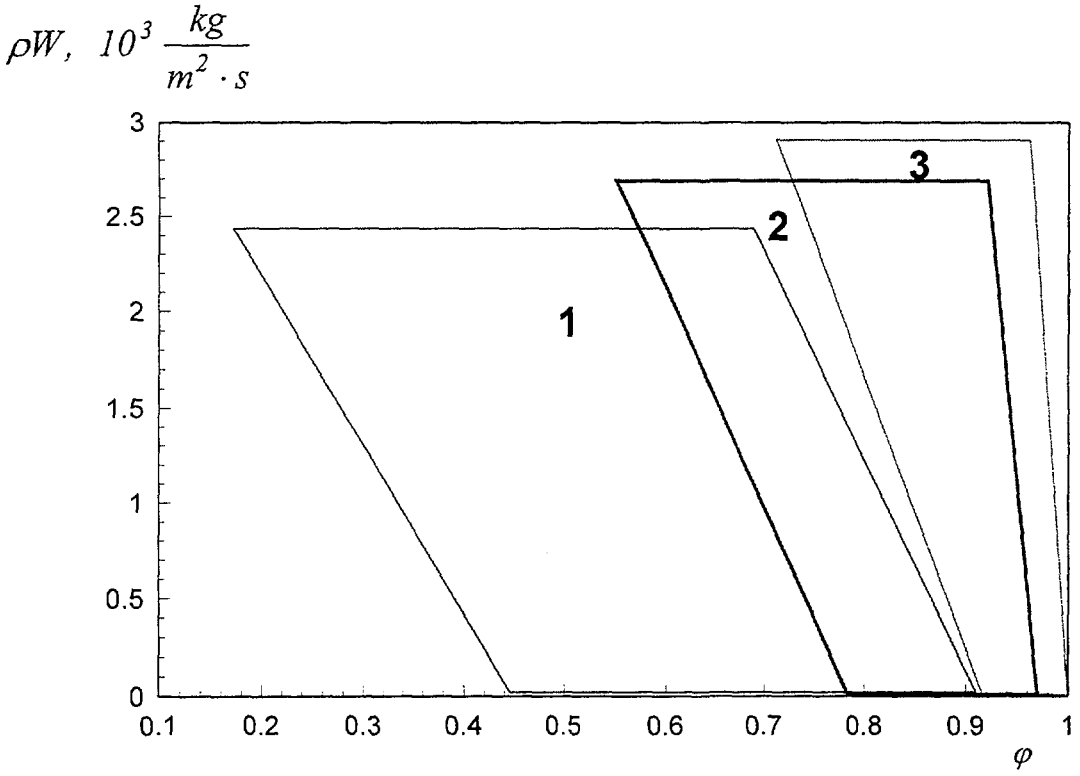

Fig. 5. The Doroschuk pattern map modified by the first method for different pressure magnitudes.
1 -- the boundary between nucleate and slug regimes;
2 -- the boundary between slug regime and disperse-annular regime with waves on the film;
3 -- the boundary between disperse-annular regime with waves on the film and disperse-annular regime with wave-likes on the film;

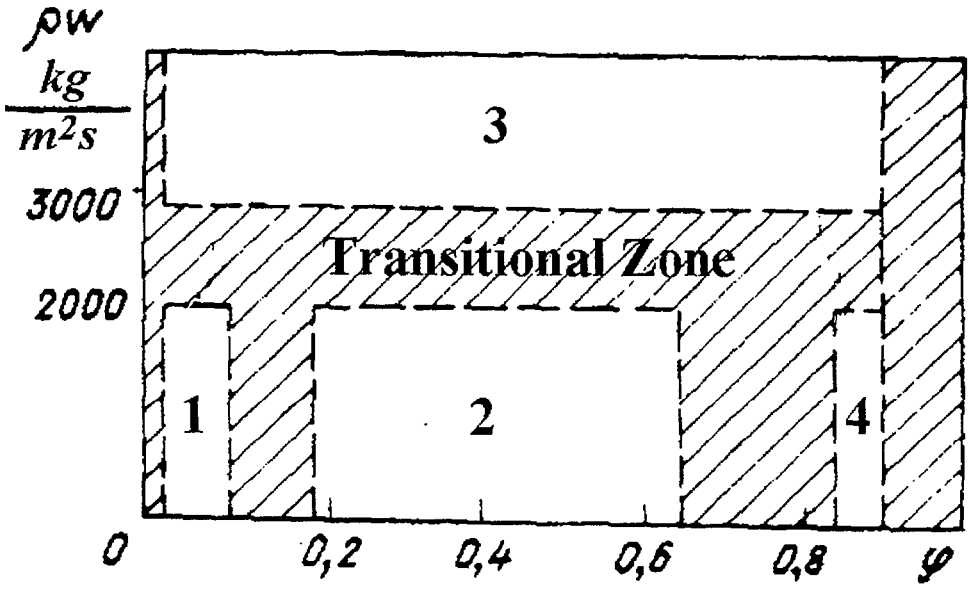

Fig. 6. The Bennett pattern map modified by the second method. Regimes:
1 – nucleate, 2 – slug, 3 – turbulence, 4 – annular.

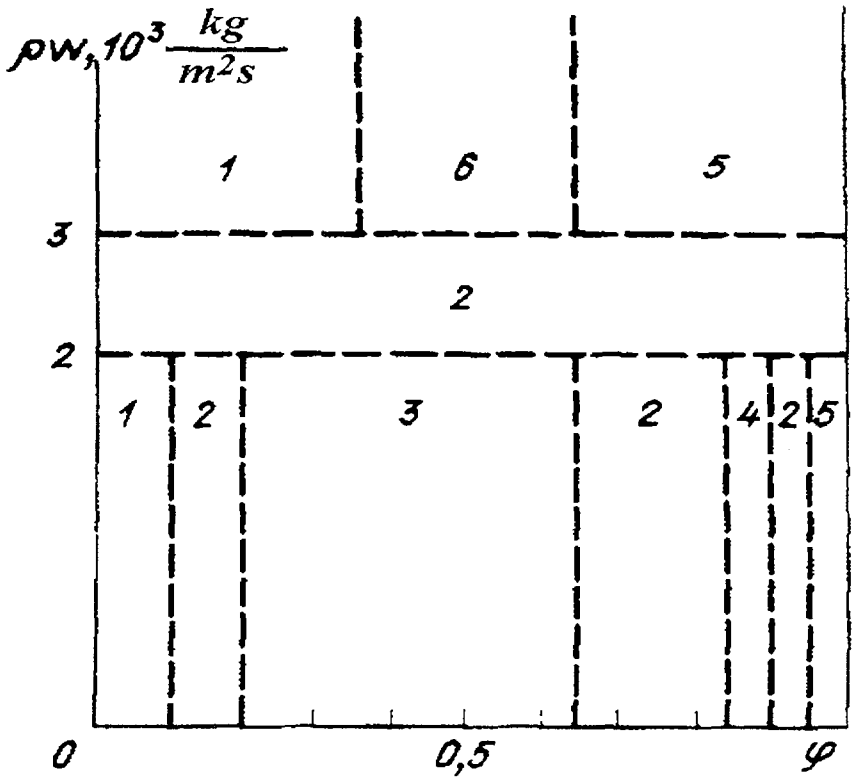

Fig. 7. The Bennett pattern map modified by the second method (for the interphase friction description). Regimes:
1 – nucleate, 2 – transitional zones, 3 – slug, 4 – annular, 5 – disperse, 6 – emulsion.

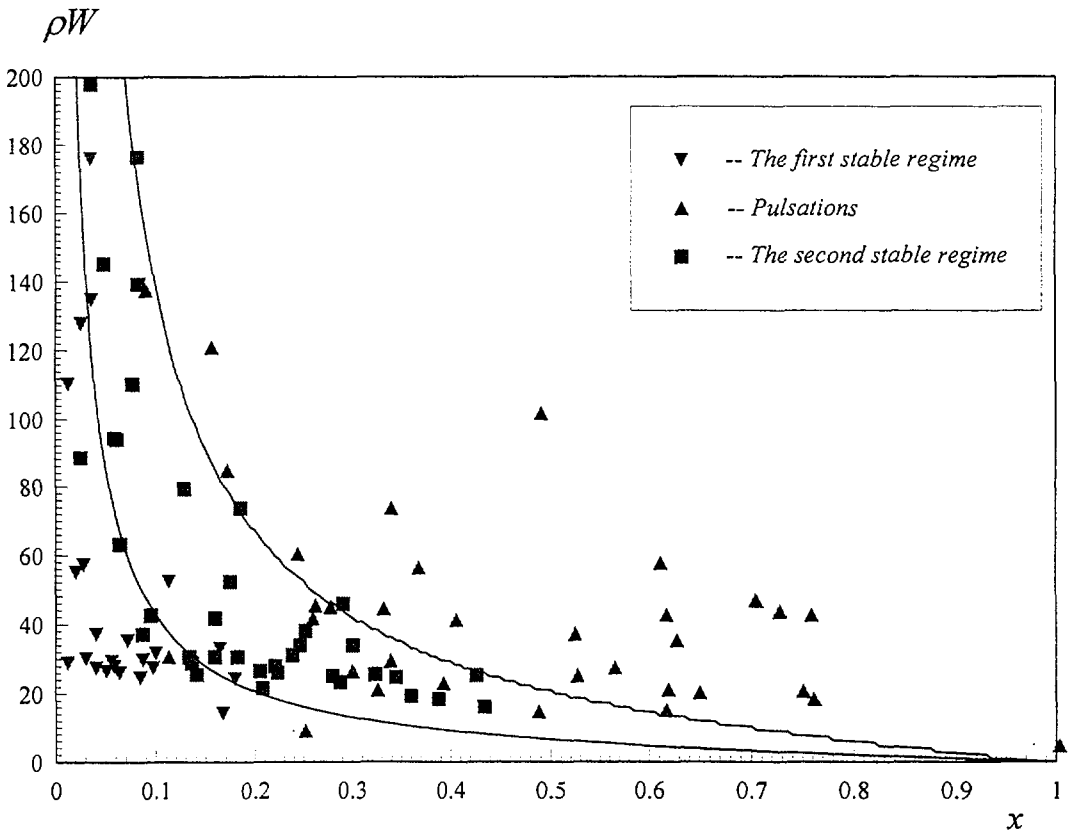

Fig. 8. Experimental pattern map constracted by Yamaguchi.

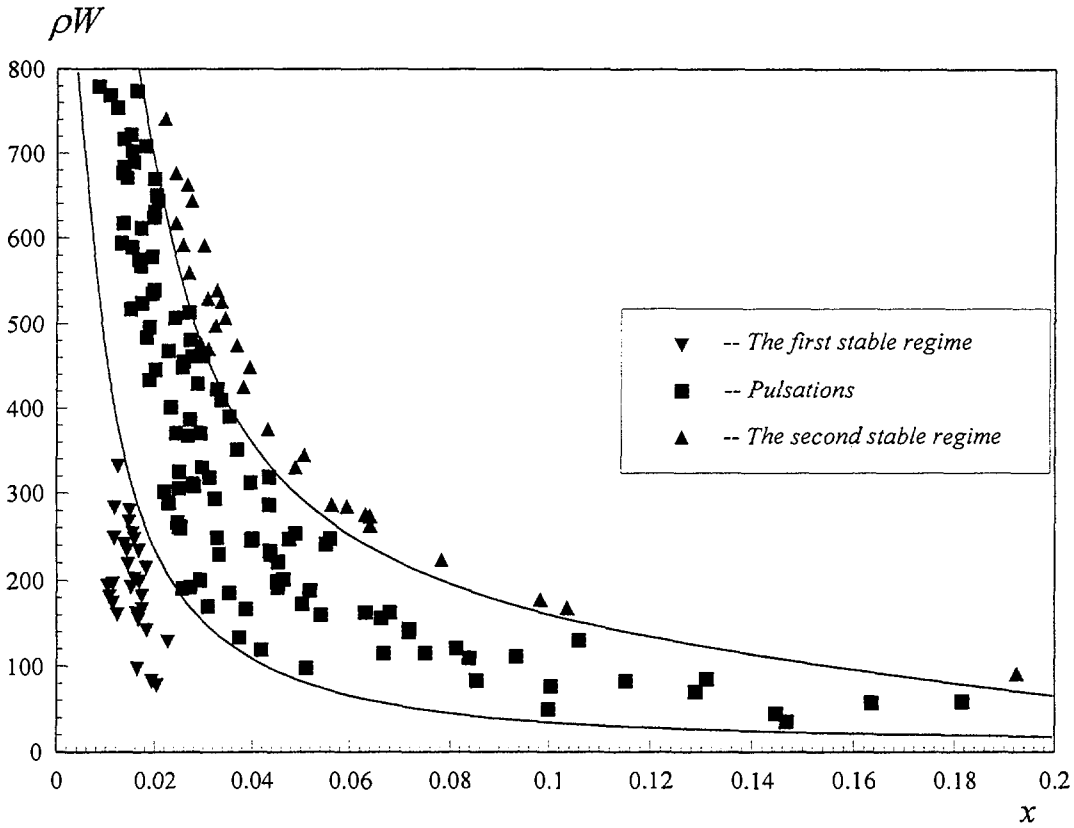

Fig. 9. Experimental pattern map, constracted in IPPE.

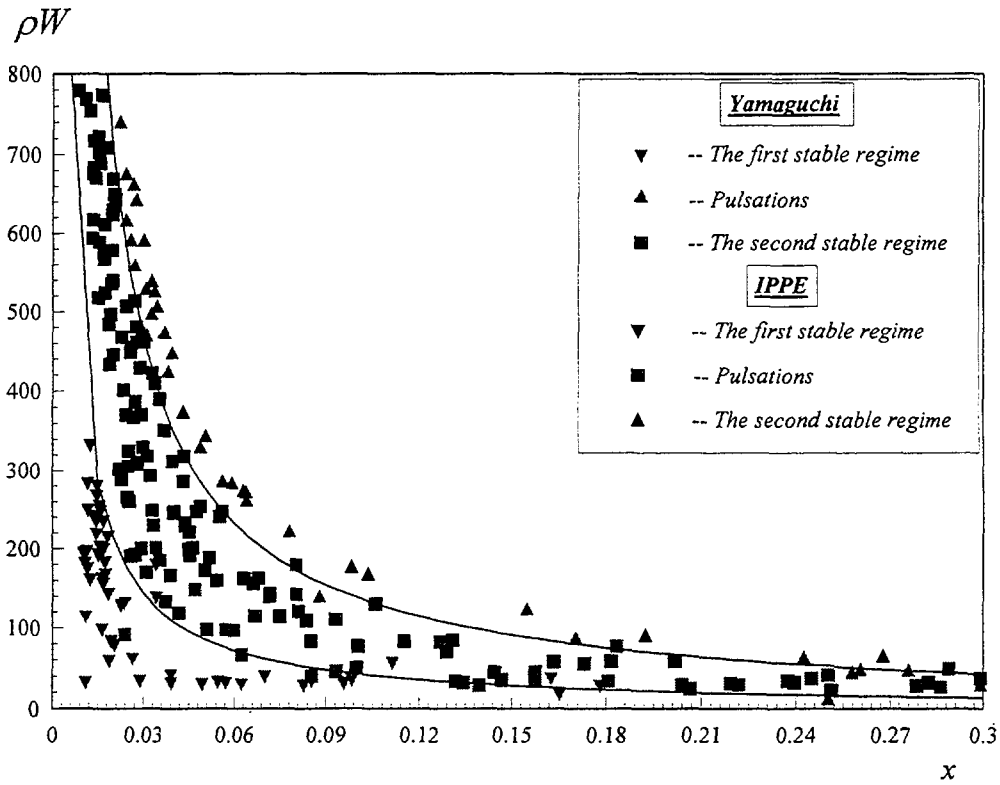

Fig. 10. The comparison of Yamaguchi pattern map and IPPE pattern map

It is necessary to note that the difficulty of regimes identification at realisation of experiments on liquid metals has reduced to the definition of flow regimes by two-phase flow stability criteria. It is known that in liquid metal two-phase flow there are the same regimes as in steam-water flows. In [18] in the analysis of experimental data on sodium boiling presented in [19] three basic boiling regimes are selected: nucleate (small steam fraction values and minor flow rate fluctuations), slug (significant fluctuations of the flow rate), disperse-annular (the drop of fluctuations and passage to stable flow is observed). Proceeding from this for a determinacy as the first approximation it is possible to put in the correspondence the first stable flow to the nucleate regime, unstable regime to the slug regime, the second stable regime to the transitional from slug to disperse-annular regime and disperse-annular regime.

Fig. 11 and 12 demonstrate the difference of Bennett and Doroschuk maps from Yamaguchi and IPPE pattern maps. It confirms the statement about essential association of regimes boundaries on many parameters, in this case from pressure and coolant properties. Hence comparison is necessary to realise on pattern maps modified by the first method and presented in coordinates (ρW, φ). The comparison of a modified Bennett map with an integrated Yamaguchi and IPPE modified map is shown on fig. 13. From fig. 13 it is visible that the modified Bennett map is not necessary for application in the liquid metal two-phase flow calculations. It is impossible adequately to modify a Doroschuk map (fig. 5) in a similar way. Therefore in a plan of calculations is it also unsuitable. Besides on fig. 14 it is shown that the approximating lines designed on the formulas (45), (46) also inadequately describe the liquid metal two-phase flow regimes boundaries.

Thus for calculation of a two-phase liquid metal flow it is necessary to use experimental pattern maps obtained just for liquid metal. We take into account the IPPE pattern map because it is obtained for the greater range of the flow rate and steam fraction magnitude than Yamaguchi pattern map. After excluding from reviewing experimental points

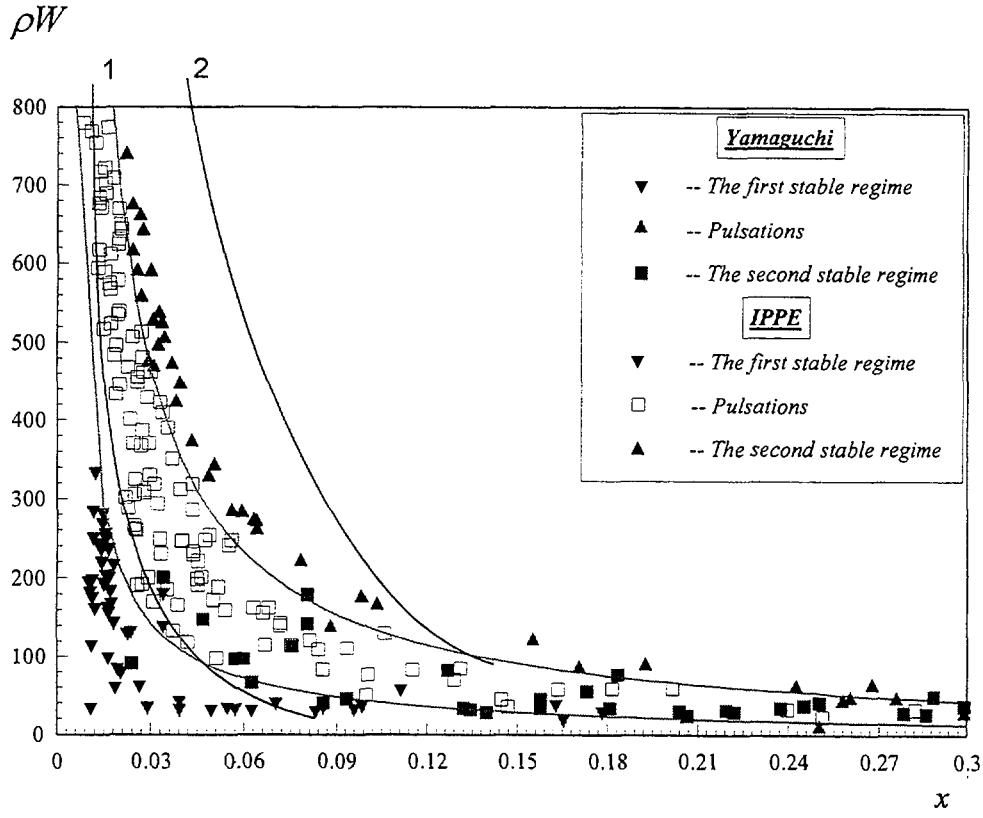

Fig. 11. The comparison of Bennett pattern map and Yamaguchi-IPPE pattern map.
1 -- the boundary between nucleate and slug regimes
2 -- the boundary between slug and emulsion regimes

with leaving only boundaries between regimes and presenting obtained map on the plot in coordinates (ρW, φ) we produce a new pattern map (fig. 15). It can be used in computer codes for calculation of the liquid metal two-phase flow characteristics at atmospheric pressure under the natural circulation conditions in the fast reactor core (heat removal conditions).

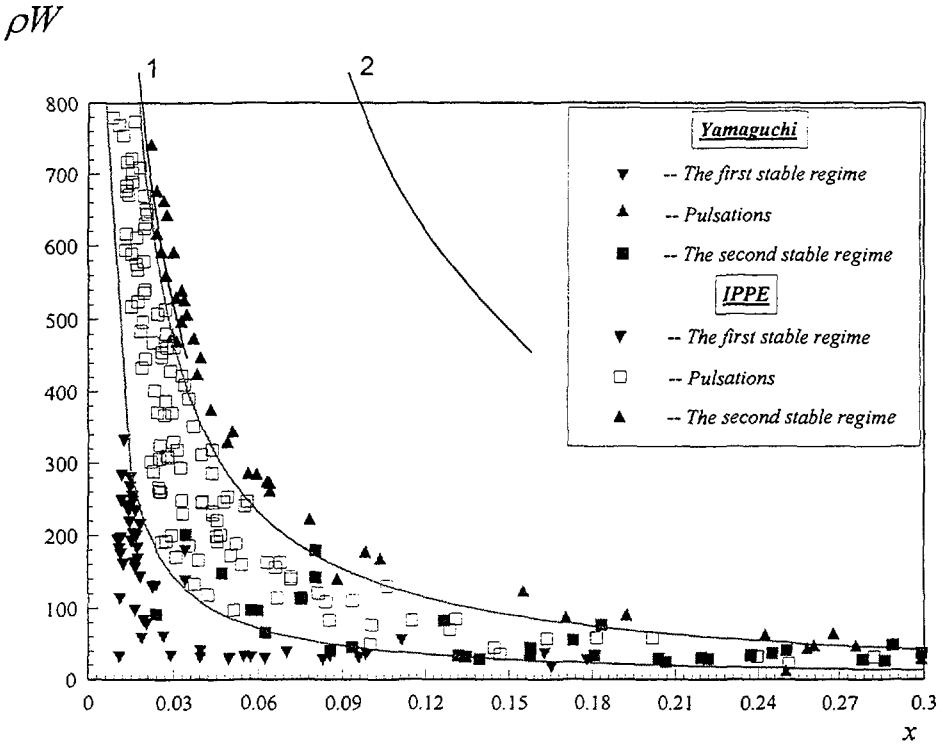

Fig. 12. The comparison of Doroschuk pattern map and Yamaguchi-IPPE pattern map.
1 -- the boundary between nucleate and slug regimes
2 -- the boundary between slug and disperse-annular regimes

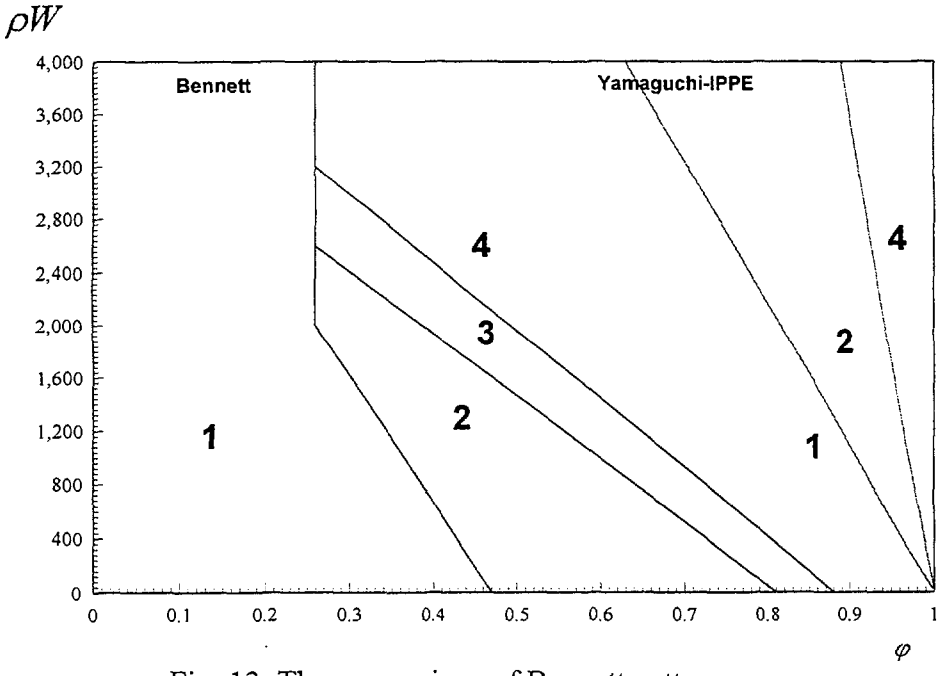

Fig. 13. The comparison of Bennett pattern map
and Yamaguchi-IPPE pattern map modified by the first method.
1 -- nucleate regime; 2 -- slug regime; 3 -- emulsion regime;
4 -- disperse-annular and annular regimes.

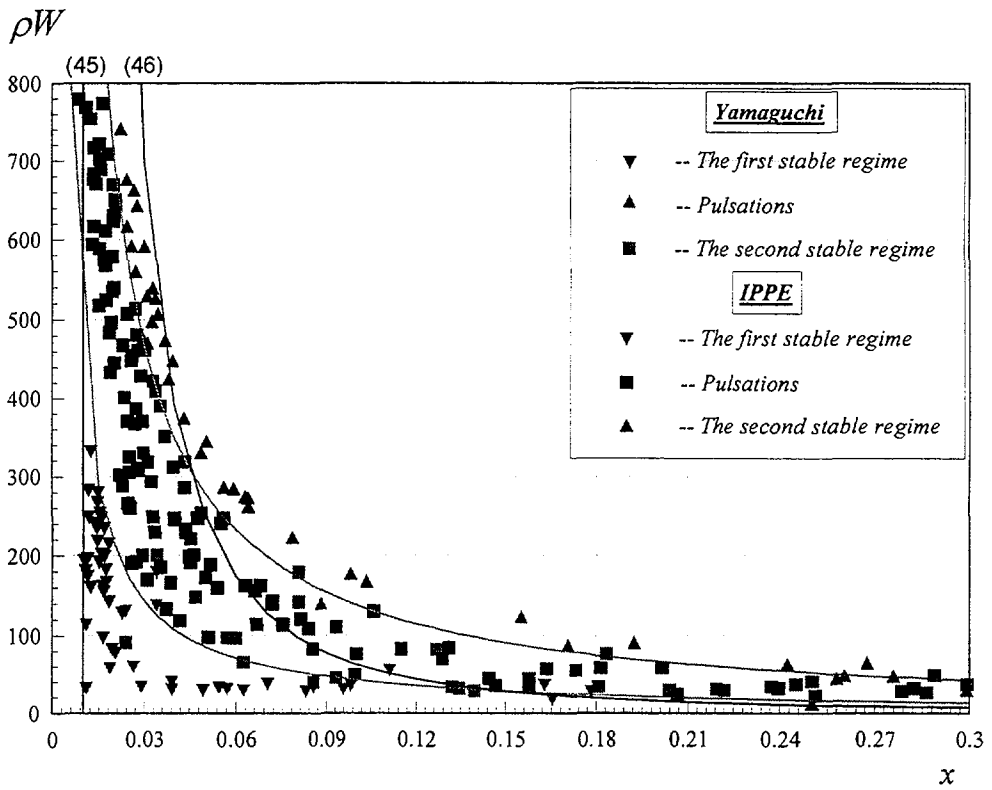

Fig. 14. The comparison of regimes boundaries calculated by formulas (45), (46), and regimes boundaries on the Yamaguchi-IPPE pattern map.

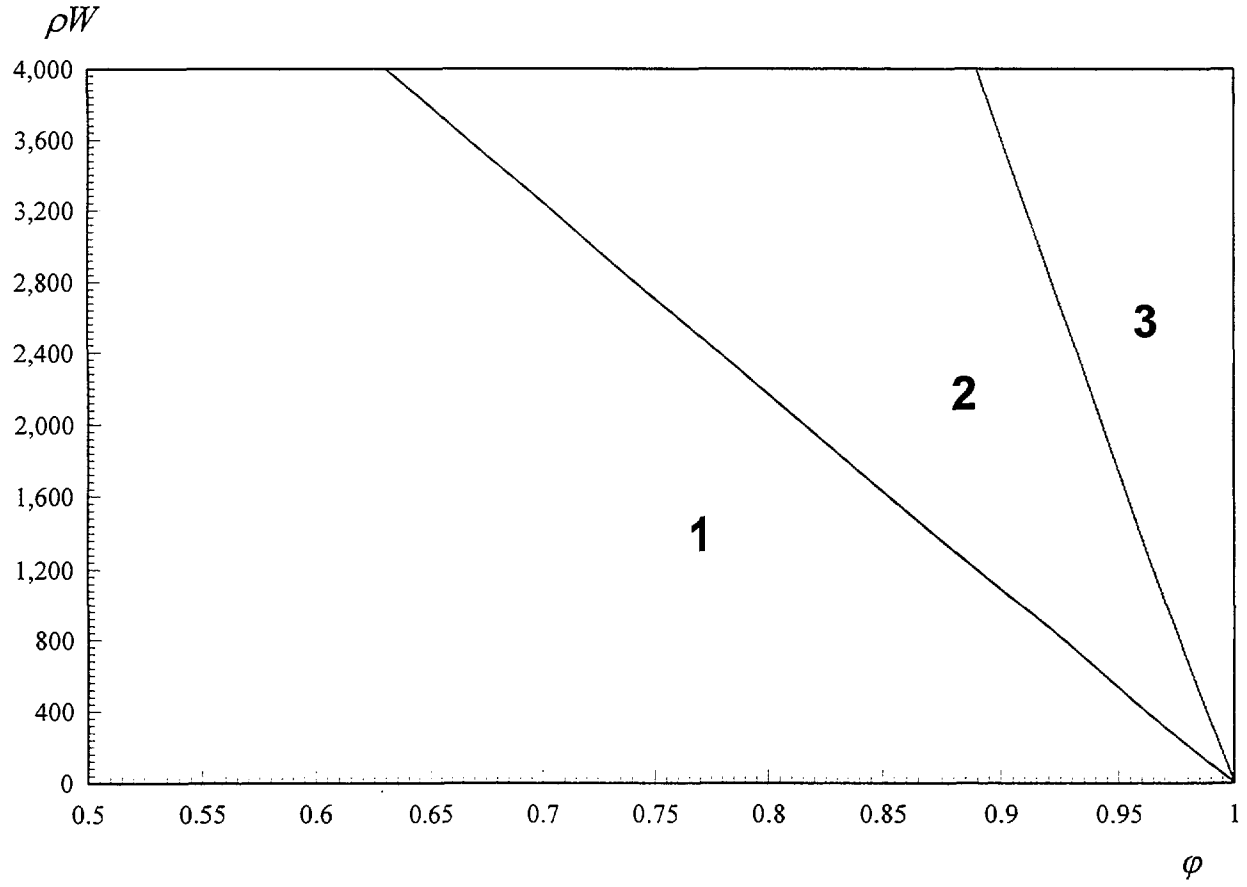

Fig. 15. The IPPE pattern map modified by the first method.
1 -- nucleate regime; 2 -- slug regime; 3 -- disperse-annular and annular regimes.

CONCLUSION

Due to detail phases interaction description and thermohydraulics of non-stationary conditions the two-fluid model is effective in calculations of non-stationary processes in nuclear reactors in various accident situations as compared, for example, with a homogeneous model. The statement of the problem presented in the paper in an approximation of equal pressure both unequal phases velocities and temperatures has the closed system of constitutive relations. This constitutive relations system is used in connection with an adjacent problem of a two-phase flow regimes boundaries definition (in this case for liquid metal flow). The difficulties in a construction of a two-fluid model for exposition of a liquid metal flow are connected basically with insufficient knowledge in the field of interphase interaction characteristics connections. It is necessary to select constitutive relations very accurately, correctly justifying their applicability for the appropriate conditions. Therefore the model presented in this paper requires the careful analysis and checking that it is possible to realise only by means of computer code creation on the basis of this model and its verification on experiments.

REFERENCES

[1] BOGOSLOVSKAYA G.P., BOGATYIRJEV I.L., ZHUKOV A.V., SOROKIN A.P., TITOV P.A. The Interphase Interaction in Two-Phase Gas-Liquid Flows in Channels. IPPE Preprint ¹ 2149, Obninsk, 1990, 43 ps (in Russian).

[2] KOUZNETSOV YU.N. Heat Exchange in the Nuclear Reactor Safety Problem. Moskow, Energoatomisdat, 1989, 296 ps (in Russian).

[3] ISHII M., MASHIMA K. Two-Fluid Model and Hydrodynamic Constitutive Relations // Nuclear Engineering and Design, 1984, v.82, ¹ 1-3, p. 107–126.

[4] RELAP5/MODL. Code Manual. v.1: System Models and Numerical Methods // NUREG/RCR – 1826, 1981.

[5] NINOKATA H., OKANO T. SABENA: Subassembly Boiling Evolution Numerical Analysis // Nuclear Engineering and Design, 1990, v.120, ¹ 3, p. 349–367.

[6] KELLY J.E., KASIMI M.S. Development of the Two-Fluid Multidimentional Code THERMIT for LWR Analysis // Heat Transfer, 1980, v.102, p. 149–162.

[7] NIGMATULLIN R.N. Fundamentals of a heterogeneous mediums mechanics. Moskow, Nauka, 1978 (in Russian).

[8] WALLIS G. One-Dimentional Two-Phase Flows. Moskow, Mir, 1972 (Translated from English to Russian).

[9] KIRILLOV P.L., YURIEV YU.S., BOBKOV V.P. The Hand Book on Thermohydraulic Clculations (nuclear reactors, heatexchangers, steamgenerators). Moskow, Energoatomisdat, 1990 (in Russian).

[10] BOGOSLOVSKAYA G.P., BOGATYIRJEV I.L., ZHUKOV A.V., SOROKIN A.P., TITOV P.A. The Two-Fluid Model for Calculation of Two-Phase Flows in Reactor Fuel Subassemblies (equations, the constitutive relations system). IPPE Preprint ¹ 2166, Obninsk, 1991, 38 ps (in Russian).

[11] BORISHANSKI V.M., KUTATELADZE S.S., NOVIKOV I.I., FEDYNSKI O.S. Liquid Metal Coolants. Moskow, Atomizdat, 1976, 328 ps (in Russian).

[12] BENNETT A.W. et al. Flow Visualisation Studies of Boiling Water at High Pressures // AERE-R4874, 1965.

[13] DOROSCHUK V.E., BOREVSKY L.JA., LEVITAN L.L. Holographic Investigation of Steam-Water Flows in Heated and Unheated Channels // Heat Transfer, Proc. VII Internat. Heat Transfer Conf., Munich, FRG, v. 5, p. 537–553.

[14] SOLBRIG C.W. et al. Heat Transfer and Friction Correlations Required to Describe Steam-Water Behavior in Nuclear Safety Studies // AIChE Symp. Ser. 1978, v. 74, ¹ 174, p. 100–128.
[15] TRAC-PD2. An Advanced Best-Estimate Computer Program for Pressurized Water Reactor Loss-of-Coolant Accident Analysis. // NUREG/CR-2054, 1981.
[16] YAMAGUCHI K. Flow Pattern and Dryout under Sodium Boiling Conditions. // Nuclear Engineering and Design, 1987, v. 99, p. 247–263.
[17] SOROKIN A.P., IVANOV YE.F., MALKOV V.L., KOLESNIK V.P., MARTSINIOUK D.YE., RYMKEVICH K.S., KORKHOV O.A. Experimental Investigations of the Heat Exchange and Stability of the Liquid Metal Boiling in the Natural Circulation Loop. IPPE Preprint ¹ 2631, Obninsk, 1997, 32 ps (in Russian).
[18] ZEIGARNIK YU.A., LITVINOV V.D. The Alcaline Metals Boiling in Channels. Moskow, Nauka, 1983 (in Russian).
[19] KIKUCHI J., HAGA K., TAKAHASHI T. Experimental Study of Steady-State Boiling of Sodium Flowing in a Single-Pin Annular Channel. // J. Nucl. Sci. and Technol., 1975, v. 12, ¹ 2, p. 83–91.