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DISTINCTIVE FEATURES OF THE MODEL OF THE DRIFT OF PHASES USED IN COMPUTATIONAL DYNAMIC REACTOR PROGRAMS

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We present relations of the overall model of drift for use in dynamic reactor programs. On the boundaries that separate the sets of conditions of a two-phase flow, a smooth transition is achieved between the drift velocity relations corresponding to different regimes. The relations suggested can be used for vertical channels of various geometries with ascending and descending motion of a coolant in a wide range of flow velocities.

At new-generation nuclear power plants (NPP) with passive safety systems the emergency cooling of a reactor with depressurization of the primary circuit occurs at very low flow rates of natural circulation (NC) with boiling of the coolant in the core, two-phase flow in other elements of the circulation loop, and possible reversal of the coolant flow. In this case the reliability of the cooling of the core is determined by hydrodynamic and thermal processes in all of the elements of the NC loop: dynamic and thermal nonequilibrium state of the two-phase flow, vapor content and hydraulic resistance, which depend on the modes of the two-phase flow, stability of its motion, heat transfer rate, and crisis processes. In essence, knowledge of the above characteristics determines the computation accuracy in predicting the parameters of the reactor plant.

At the present time, in order to determine the hydrodynamic characteristics of a two-phase flow extensive use is made of the model of the drift of phases [1]. At high velocities of a two-phase mixture (many times greater than the drift velocity) the patterns of flow and the heat transfer and hydrodynamics of the flow are determined for the most part by the discharge characteristics (reduced liquid and vapor velocities). At moderate and low mixture velocities commensurable with the drift velocity, i.e., when gravity forces start to exert a substantial effect on the hydrodynamic and thermal processes, the characteristics of a two-phase flow begin to depend not only on the magnitude of the mixture flow rate but also on the slip ratio, the distribution of the phases over the flow cross section, the orientation of the channel in space, and the direction of the coolant motion in the channel.

An adequate mathematical description of the two-phase flow characteristics requires knowledge of the relationships that make it possible to establish:

the boundaries of the two-phase flow regimes with allowance for the channel orientation in space and the direction of coolant motion;

the drift velocity and the distribution parameter corresponding to different regimes of flow, which, together with discharge characteristics, determine the void fraction.

In using the aforementioned characteristics of a two-phase flow in general computational programs for a reactor it is necessary to take into account the following fact. In long heated channels and in unheated channels under unsteady-state conditions, several regions with different flow regimes can exist simultaneously along the two-phase coolant flow; they are displaced along the channel in time. Since the relations that determine the characteristics of a two-phase flow for different flow regimes can even differ structurally, it becomes necessary to match them by introducing buffer zones within the limits of which a smooth transition from one relation to the other is accomplished.

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With allowance made for the above, we will determine relations for the drift velocity V_{vj} and the distribution parameter C_0. Knowing these characteristics at given values of the reduced vapor and mixture velocities makes it possible to determine the void fraction of the two-phase flow

$$\varphi = \frac{j_v}{C_0 j + V_{vj}}. \tag{1}$$

First, let us consider a vertical channel with an ascending coolant flow. For this case the following flow patterns are generally accepted: bubble, slug, frothing (swirled), annular, and mist-annular regimes.

At the present time, the most theoretically justified procedure for determining the boundaries between the patterns of a vertical ascending flow in unified coordinates is given in [2].

The distribution parameter C_0 for all of the regimes of a vertical ascending two-phase flow is determined from the relation [2]:

for a tube

$$C_0 = [1.2 - 0.2\,(\rho_v/\rho_{liq})^{1/2}]\,[1 - \exp(-18\varphi)], \tag{2}$$

for a rectangular channel

$$C_0 = [1.35 - 0.35\,(\rho_v/\rho_{liq})^{1/2}]\,[1 - \exp(-18\varphi)]. \tag{3}$$

Accounting for the fact that the quantity C_0 should tend to 1 when $\varphi \to 1$, the relation for C_0 can be approximated in the following way:

$$C_{0,1} = \begin{cases} C_0 & \text{when} \quad \varphi \le 0.8\,, \\ \dfrac{C_0}{1 + 5\,(C_0 - 1)\,(\varphi - 0.8)} & \text{when} \quad \varphi > 0.8\,. \end{cases} \tag{4}$$

In [2], from the condition of the most probable coalescence of vapor bubbles it is found that the value of the void fraction $\varphi_{b.1-2} = 0.3$ corresponds to the boundary of the transition from the bubble to the slug regime of flow, which agrees well with experimental data.

Thus, in a two-phase flow in the range of void fractions $\varphi \in [0; 0.3]$ the bubble regime is realized, for which the drift velocity is equal to [1]

$$V_{vj,1} = \sqrt{2}\left[\frac{\sigma g\,(\rho_{liq} - \rho_v)}{\rho_{liq}^2}\right]^{1/4} (1 - \varphi)^{1.75}. \tag{5}$$

With account for the value of $\varphi_{b.1-2}$ and relations (1) and (5), the boundary between the bubble and slug patterns of flow in the coordinates j_{liq}–j_v has the form

$$j_{liq}^{b.1-2} = \left[\frac{3.333}{C_0} - 1\right] j_v^{b.1-2} - \frac{0.76}{C_0}\left[\frac{\sigma g \Delta\rho}{\rho_{liq}^2}\right]^{1/4}. \tag{6}$$

Let us consider the boundary between the slug and frothing (swirled) regimes. In [2] the boundary is determined from the condition of the stability of countercurrent motion of vapor in a slug and in the liquid surrounding it. From this condition and upon taking into account the fact that the drift velocity in the slug regime of flow in a tube [1] amounts to

$$V_{vj,2} = 0.35 \left[\frac{g\Delta\rho D}{\rho_{liq}} \right]^{1/2}, \tag{7}$$

the following expression was obtained in [2] for the void fraction $\varphi_{b.2-3}$, which determines the boundary of transition from the slug to the frothing pattern of flow:

$$\varphi_{b.2-3} = 1 - 0.813 \left\{ \frac{(C_0 - 1)\, j + 0.350 \sqrt{g\Delta\rho D/\rho_{liq}}}{j + 0.75 \sqrt{g\Delta\rho D/\rho_{liq}}\, (g\Delta\rho D^3/\rho_{liq}\, \nu_{liq}^2)^{1/18}} \right\}^{0.75}. \tag{8}$$

For slightly viscous fluids, such as water, $(g\Delta\rho D^3/\rho_{liq}\nu_{liq}^2)^{1/18} \approx 3$; it depends weakly on the pressure and the channel diameter.

Then, assuming that $C_0 \approx 1.2-1.35$ we have

$$\varphi_{b.2-3} = 1 - 0.813\,(0.2 \div 0.35)^{0.75} \left[\frac{j + (1 \div 1.75) \sqrt{g\Delta\rho D/\rho_{liq}}}{j + 2.25 \sqrt{g\Delta\rho D/\rho_{liq}}} \right]^{0.75}. \tag{9}$$

According to relation (9), $\varphi_{b.2-3}$ can range from 0.65 to 0.76, and therefore we assume that $\varphi_{b.2-3} = 0.70$.

Using the value $\varphi_{b.2-3}$ and relation (1), the boundary between the slug and frothing regimes of flow in the coordinates $j_{liq}-j_v$ can be presented in the form

$$j_{liq}^{b.2-3} = \left[\frac{1.43}{C_0} - 1 \right] j_v^{b.2-3} - \frac{1}{C_0} V_{vj,2}. \tag{10}$$

In general, within the range of void fractions $\varphi \in [0.3; 0.7]$ in a two-phase flow, where the slug regime is realized, with allowance for surface tension forces the drift velocity has the form [1]

$$V_{vj,2} = K_1 \left[\frac{g\Delta\rho L}{\rho_{liq}} \right]^{1/2} \left\{ 1 - \exp\left[(3.37 - 0.401\, Bo_1^2)\cdot 10^{-1}\right] \right\}, \tag{11}$$

where

$$Bo_1 = \begin{cases} 2.9 & \text{for} \quad Bo \le 2.9\,, \\ Bo & \text{for} \quad Bo > 2.9\,. \end{cases}$$

The greatest difficulties arise when one determines the coefficient K_1 and the characteristic dimension L for channels with a complicated shape, in particular, for rod assemblies. In [3] a universal approach is suggested that allows one to formalize the selection of the characteristic dimension for channels of complicated geometry. As this dimension, a quantity is suggested equal to half the wetted perimeter $\Pi/2$. Then for a circular tube $L_t = \pi D/2$, for a rectangular channel $L_r = 2(a + b)/2$, for an annular channel $L_{ann} = \pi(D_{in} + D_{out})/2$, and for a rod assembly $L_{ass} = \pi(D_{bat} + nd_{f.el})/2$.

With such a definition of the characteristic dimension, a dependence was obtained in [3] for the drift velocity in the slug regime of flow:

$$\frac{V_{vj,2}}{\left[\frac{g\Delta\rho L}{\rho_{liq}} \right]^{1/2}} = \begin{cases} 0.28z\, [1 - \exp([3.37 - 0.401\, Bo_1^2]\cdot 10^{-1})] & \text{for} \quad z \le 1\,, \\ 0.28\, [1 - \exp([3.37 - 0.401\, Bo_1^2]\cdot 10^{-1})] & \text{for} \quad z > 1\,, \end{cases} \tag{12}$$

where $z = 6.2[2\delta/\Pi]^{1/2}$; $\delta = a$ for a rectangular channel; $\delta = (D_{out} - D_{in})/2$ for an annular channel; $\delta = D/2$ for a circular tube; and $\delta = d_{eq}/2$ for a bundle of rods.

Relation (12) for a circular tube yields the well-known relationship for the drift velocity (7).

However, the slug regime of flow is not always located between the boundaries of the bubble ($\varphi_{b.1-2}$) and frothing ($\varphi_{b.2-3}$) regimes. At large mass velocities the region of the frothing two-phase flow may degenerate, and then the slug regime may undergo a direct transition to the annular mode. The boundary of this transition may lie within the range $0.3 < \varphi_{b.2-4} \leq 0.7$. The mechanism behind the transition from the slug to the annular flow involves the hydrodynamic destruction of the links between the slugs and the stripping of drops from the crests of waves on the vapor-liquid interface.

The criterion of transition from the slug to the annular pattern of flow is given in [2]:

$$\frac{\mu_{liq} j_v}{\sigma} \sqrt{\left(\frac{\rho_v}{\rho_{liq}}\right)} = N_\mu^{0.8}, \tag{13}$$

where $N_\mu = \mu_{liq} / [\rho_{liq}\sigma\sqrt{\sigma/g\Delta\rho}\,]^{1/2}$.

Criterion (13) permits one to determine the reduced vapor velocity corresponding to the boundary between the slug and annular regimes of flow:

$$j_v^{b.2-4} = \left[\frac{\sigma g \Delta\rho}{\rho_v^2}\right]^{1/4} N_\mu^{-0.2}. \tag{14}$$

With allowance for Eqs. (10) and (14), the reduced liquid velocity corresponding to the boundary between the slug and annular patterns of flow has the form

$$j_v^{b.2-4} = \left[\frac{1.43}{C_0} - 1\right] \left[\frac{\sigma g \Delta\rho}{\rho_v^2}\right]^{1/4} N_\mu^{-0.2} - \frac{1}{C_0} V_{vj,2}. \tag{15}$$

In the coordinates $j_{liq} - j_v$ the boundary between the slug and annular flow regimes is determined from relations (14) and (15). As shown above, when $j_{liq} < j_{liq}^{b.2-4}$, the slug pattern of flow goes over into the frothing one at $\varphi_{b.2-3} = 0.7$.

For the frothing and annular modes of flow the drift velocity is determined from the well-known relation [1]

$$V_{vj,3,4} = \sqrt{2} \left[\frac{\sigma g \Delta\rho}{\rho_{liq}^2}\right]^{1/4}. \tag{16}$$

The boundaries of the flow regimes for a steam-water flow in a vertical tube with $D = 0.02$ m at the pressures $P = 0.1$ and 4 MPa constructed from relations (6), (10), (14), and (15) are presented in Fig. 1. From the figure it is seen that an increase in pressure deforms substantially the boundaries separating the flow regimes and leads to contraction of the boundary of transition from the annular to the frothing regime of flow. Thus, at $P = 0.1$ MPa, the slug pattern of flow passes directly into the annular one when $\rho w \geq 5460$ kg/(m^2·sec), and at $P = 4$ MPa this occurs when $\rho w \geq 860$ kg/(m^2·sec).

With allowance for the relationships given above, we may suggest an overall model for determining the drift velocity. The model has smooth transitions through the boundaries separating different regimes of two-phase flow in a vertical channel with ascending motion of the coolant:

$$V_{vj}^{asc} = V_{vj,1} + [V_{vj,2} - V_{vj,1}](1 - \exp[-b(\varphi^* - 0.25)]) +$$

$$+ [V_{vj,3,4} - V_{vj,2}](1 - \exp[-b(\varphi^{**} - K)]), \tag{17}$$

where $K = 0.7 - 3\cdot 10^{-4}(\rho w^* - \rho w_0)$; $b = 100$;

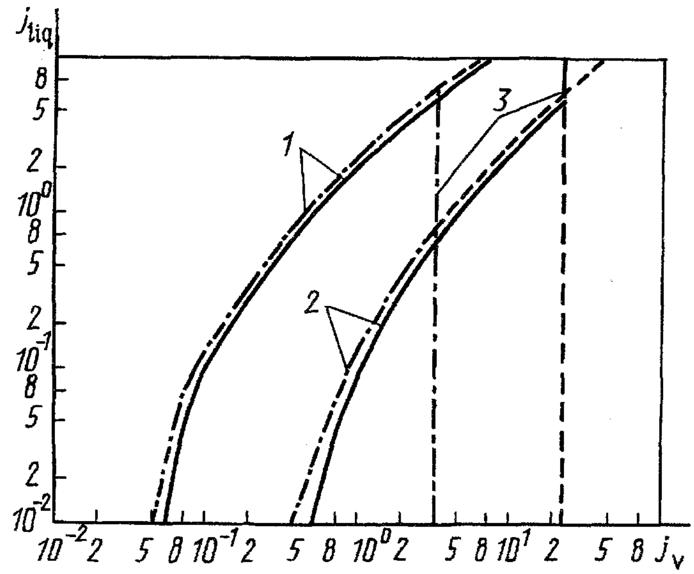

Fig. 1. Boundaries of the two-phase flow regimes in a vertical channel with ascending flow of a coolant in the coordinates $j_{liq} - j_v$: solid curves, $P = 0.1$ MPa; dash-dot curves, $P = 4$ MPa; 1) boundary between the bubble and slug regimes of flow, Eq. (6); 2) boundary between the slug and frothing regimes of flow, Eq. (10); 3) boundary between the slug and annular regimes of flow, Eqs. (14), (15). j_v, j_{liq}, m/sec.

$$\rho w^* = \begin{cases} \rho w_0 & \text{when} \quad |\rho w| \le \rho w_0 , \\ |\rho w| & \text{when} \quad |\rho w| > \rho w_0 ; \end{cases} \qquad \varphi^* = \begin{cases} 0.25 & \text{when} \quad \varphi \le 0.25 , \\ \varphi & \text{when} \quad \varphi > 0.25 ; \end{cases}$$

$$\varphi^{**} = \begin{cases} K & \text{when} \quad \varphi \le K , \\ \varphi & \text{when} \quad \varphi > K ; \end{cases} \qquad \rho w_0 = \left(\left[\frac{1.43}{C_0} - 1 \right] \rho_{liq} + \rho_v \right) \times \left[\frac{\sigma g \Delta\rho}{\rho_v^2} \right]^{1/4} N_\mu^{-0.2} = \frac{\rho_{liq}}{C_0} V_{vj,2} .$$

For the aforementioned conditions the distribution parameter is determined from relation (4).

The two-phase flow parameters were investigated in [4] in the absence of forced flow of the coolant ($j = j_v$). The analysis of theoretical and computational investigations performed in [4] made it possible to reveal the following features:

the ranges of void fractions that determine the bubble, slug, and annular regimes of flow in the absence of forced motion of the coolant and in an ascending flow coincide;

the drift velocities in the indicated three regimes of a two-phase flow in the absence and presence of ascending forced flow of the coolant are determined from identical relations (relation (17) may be used);

for the conditions considered the distribution parameter C_0 differs from the values recommended for an ascending flow; this is due to the specific features of the hydrodynamics of flow in the absence of forced flow of the coolant.

According to the recommendation given in [4], at low pressures, which are typical for conditions of absence of forced flow of the coolant, the parameter C_0 can be calculated from the relation

$$C_{02} = \frac{3}{1 + 2\varphi} . \tag{18}$$

For a smooth transition from relation (4) in the case of forced ascending flow of the coolant Eq. (18) can be supplemented with the relation

$$C_{03} = C_{01} + (C_{02} - C_{01}) \, [1 - \exp(0.1 \, [(\rho w)_1 - 50])] , \quad (\rho w) \ge 0 , \tag{19}$$

where

$$(\rho w)_1 = \begin{cases} 50 \ \text{kg/(m}^2\cdot\text{sec)} & \text{when} \quad \rho w \geq 50 \ \text{kg/(m}^2\cdot\text{sec)}, \\ \rho w & \text{when} \quad 0 < \rho w < 50 \ \text{kg/(m}^2\cdot\text{sec)}. \end{cases}$$

Let us now consider the characteristics of a two-phase flow in the case of descending motion of the coolant phases, which were investigated in detail in [5, 6].

In the case of gravitational descending motion of a two-phase coolant one clearly distinguishes three flow regimes: 1) bubble regime, 2) slug regime, and 3) annular regime. Moreover, the annular regime is divided into two subregimes: falling film and mist-annular.

At small reduced liquid velocities the falling film regime is realized in a descending flow. In this regime the liquid flows down the channel wall under the influence of gravity, whereas the gas (or vapor) flow moves along the central portion of the channel virtually without interacting with the liquid film.

The falling film regime can go over into the bubble or slug and mist-annular regimes.

At small reduced vapor velocities ($j_v/j_{liq} < 2$) an increase in j_{liq} can lead to disturbance of the stable gravitational fall of the film. The resulting waves interact with the vapor core, and the annular flow goes over into a bubble or slug flow. From the condition of disturbance of the stability of gravitational film fall a relation was obtained in [6] for determining the boundary of the transition from the falling film to the bubble or slug flow regime:

$$\mathrm{Fr}_{liq}^{b.5-1,2} = (0.77 - 9.2\ \mathrm{Bo}^{-2})^{1.278} \quad \text{when} \quad j_v/j_{liq} < 2 \tag{20}$$

or

$$j_{liq}^{b.5-1,2} = (0.77 - 9.2\ \mathrm{Bo}^{-2})^{1.278} \left[\frac{g\Delta\rho L}{\rho_{liq}}\right]^{1/2} \quad \text{when} \quad j_v < 2 j_{liq}^{b.5-1,2}. \tag{21}$$

In the falling film regime at a constant reduced liquid velocity ($j_{liq} < j_{liq}^{b.5-1,2}$) an increase in the reduced vapor velocity leads, at a certain value of $j_v^{b.5-4}$, to the hydrodynamic stripping of droplets from the film surface and to the transition to a mist-annular pattern of flow. The relationship between the parameters that determines the boundary between the film and mist-annular regimes was obtained in [6] in the form

$$\mathrm{Fr}_{liq}^{b.5-4} = 1.2\ (j_v/j_{liq})^{-1.1} \quad \text{when} \quad j_{liq} < j_{liq}^{b.5-1,2}. \tag{22}$$

From Eq. (22) it is seen that the reduced vapor velocity at the boundary depends only slightly on the reduced liquid velocity. Therefore, the condition for this boundary can be approximately written in the form

$$j_{liq}^{b.5-4} = 1.2 \left[\frac{g\Delta\rho L}{\rho_{liq}}\right]^{1/2} \quad \text{when} \quad j_{liq} < j_{liq}^{b.5-1,2}. \tag{23}$$

In order to determine the void fraction $\varphi_{b.1-2}$ corresponding to the boundary of transition from the bubble to the slug pattern of flow with descending motion of the coolant, the following trends were taken into account in [5]:

vapor bubbles concentrate near the tube axis, the maximum of the void fraction lies at the relative radius $\overline{R} = 0.5$, and thereafter, as $\overline{R}$ increases, it has a slight saddle shape;

the value of φ on the tube axis at which the transition from the bubble to the slug pattern of flow is most probable amounts to $\varphi = 0.3$, just as in the case of an ascending flow. With allowance for the radial distribution of φ in the channel, the boundary value of the void fraction on transition from the bubble to the slug regime of flow with descending motion of the coolant amounts to $\varphi_{b.1-2} = 0.175$.

Then, using the value of $\varphi_{b.1-2}$, the drift velocity for the bubble pattern of flow (5), and relation (1), we obtain a relationship between the reduced vapor and liquid velocities on the boundary of the transition from the bubble to the slug pattern of flow:

$$j_{liq}^{b.1-2} = \left[\frac{5.71}{C_0^{des}} - 1 \right] j_v^{b.1-2} - \frac{1}{C_0^{des}} \left[\frac{\sigma g \Delta\rho}{\rho_{liq}^2} \right]^{1/4} \quad \text{when } j_{liq} > j_{liq}^{b.5-1,2}. \tag{24}$$

For descending motion of the phases, the distribution parameter C_0^{des} is determined from the relation [5]

$$C_0^{des} = 1.2 - [2.95 - 1135 \cdot \mathrm{Bo}^{-2.6}]^{-1}. \tag{25}$$

For a smooth transition from relation (25) to relation (18) in the absence of forced flow we may use the relation

$$C_{04} = C_0^{des} + (C_{02} - C_0^{des}) \, [1 - \exp(0.1 \, [(\rho w)_1 - 50])], \quad \rho w < 0, \tag{26}$$

where

$$(\rho w)_1 = \begin{cases} 50 \ \mathrm{kg/(m^2 \cdot sec)} & \text{for } \rho w < -50 \ \mathrm{kg/(m^2 \cdot sec)}, \\ |\rho w| & \text{for } -50 \ \mathrm{kg/(m^2 \cdot sec)} < \rho w < 0. \end{cases}$$

The signs of the reduced vapor and liquid velocities in formula (24) depend on the direction of motion of the corresponding phases.

For the boundary of the transition from the slug to the annular pattern of flow (when $j_{liq} > j_{liq}^{b.5-1,2}$) the following relation was obtained in [5]:

$$\left(\frac{j_v}{j_{liq}} \right)_{b.2-4} = \left[1 - \frac{K_1}{C_0} \frac{1}{\mathrm{Fr}_{liq}} \right] \left\{ \frac{1}{[1 - (2C_w \mathrm{Fr}_{liq}^2)^{7/23}] \, C_0} - 1 \right\}^{-1}, \tag{27}$$

where $C_w = 0.005$ is the coefficient of friction on the wall.

The function $f(\mathrm{Fr}_{liq})$ on the right-hand side of relation (27) can be roughly approximated by the simple relation

$$f(\mathrm{Fr}_{liq}) = \frac{1.2}{\mathrm{Fr}_{liq}}. \tag{28}$$

Then

$$j_v^{b.2-4} = 1.2 \left[\frac{g \Delta\rho L}{\rho_{liq}} \right]^{1/2} \quad \text{when } j_{liq} > j_{liq}^{b.5-1,2}. \tag{29}$$

From Fig. 2 it is seen that the proposed relations (21), (23), (24), and (29) predict rather well the boundaries of the flow regimes in a vertical channel in the case of descending motion of the coolant. Moreover, these relations permit one to construct in the coordinates $j_{liq} - j_v$ boundaries of flow regimes that (just as for ascending motion of the coolant) have a simple form (Fig. 3).

In the falling film regime the void fraction is independent of the reduced vapor flow rate and is determined by the relation [5]

$$\varphi = 1 - (0.016 \, \mathrm{Fr}_{liq}^2)^{7/23}, \tag{30}$$

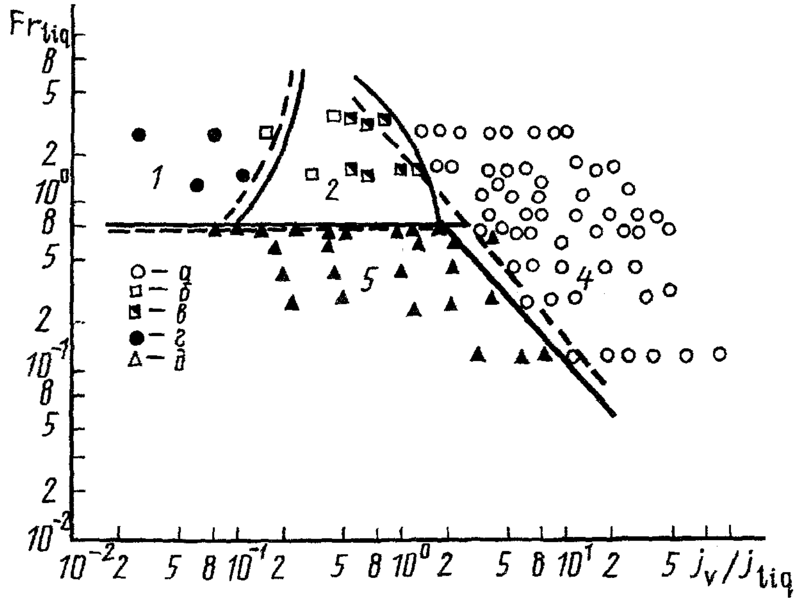

Fig. 2. Boundaries of the two-phase flow regimes in a vertical channel with descending motion of a coolant in the coordinates $Fr_{liq} - j_v/j_{liq}$: solid curves, calculation by the technique of [5, 6]; dashed curves, calculation by the present simplified technique, Eqs. (21), (23), (24), (29); 1, 2, 4, 5) regions of bubble, slug, mist-annular, and falling film regimes of flow, respectively; dots, experimental data: a) mist-annular; b) slug; c) transient regime between the slug and mist-annular regimes; d) bubble; e) falling film regime.

and therefore for this regime the concept of drift velocity loses meaning. However, to unify the computational scheme, it is possible, by using relation (1), to introduce the frictitious drift velocity

$$V_{vj,5} = -C_0 j + \frac{j_v}{1-(0.016\, Fr_{liq}^2)^{7/23}}. \tag{31}$$

In the case of descending gravitational motion of the coolant, the drift velocity in the bubble, slug, and mist-annular regimes of flow is determined from relations (5), (12), and (16), respectively.

Taking into account the above relations and the chart of flow modes (Fig. 3), the overall model for determining the drift velocity in gravitational descending motion of a coolant can be presented in the form

$$\begin{aligned} V_{vj}^{des} = b_1 \Big\{ & V_{vj,1} + (V_{vj,2} - V_{vj,1})\, [1 - \exp(-b\, [\varphi^* - 0.15])] + \\ & + (V_{vj,3,4} - V_{vj,2})\, [1 - \exp(-b\, [j_v^* - j_v^{b.2-4}])] \Big\} + \\ & + (1 - b_1) \Big\{ V_{vj,5} + (V_{vj,3,4} - V_{vj,5})\, [1 - \exp(-b\, [j_v^* - j_v^{b.5-4}])] \Big\}, \end{aligned} \tag{32}$$

where $b_1 = 1 - \exp(-b\, [j_{liq}^* - j_{liq}^{b.5-1,2}])$;

$$\varphi^* = \begin{cases} 0.15 & \text{when } \varphi \le 0.15, \\ \varphi & \text{when } \varphi > 0.15; \end{cases} \qquad j_{liq}^* = \begin{cases} j_{liq}^{b.5-1,2} & \text{when } |j_{liq}| \le j_{liq}^{b.5-1,2}, \\ |j_{liq}| & \text{when } |j_{liq}| > j_{liq}^{b.5-1,2}; \end{cases}$$

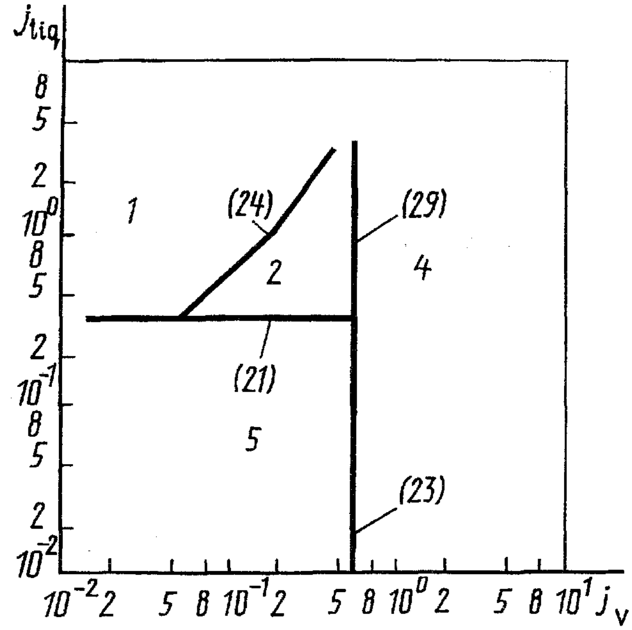

Fig. 3. Boundaries of the two-phase flow regimes in a vertical channel with descending motion of a coolant in the coordinates $j_{liq} - j_v$; the numbers 1, 2, 4, and 5 are the same as in Fig. 2; Eqs. (21), (23), (24), and (29) correspond to the boundaries that separate the regimes of flow.

$$j_v^* = \begin{cases} 1.2\left[\dfrac{g\Delta\rho L}{\rho_{liq}}\right]^{1/2} & \text{when} \quad |j_v| \le 1.2\left[\dfrac{g\Delta\rho L}{\rho_{liq}}\right]^{1/2}, \\ |j_v| & \text{when} \quad |j_v| > 1.2\left[\dfrac{g\Delta\rho L}{\rho_{liq}}\right]^{1/2}. \end{cases}$$

In the case of countercurrent motion of a two-phase coolant with forced descending motion of the liquid phase, the falling film pattern can degenerate. Depending on the magnitude of the void fraction, the bubble, slug, and annular modes of flow are realized, the boundaries between which are determined by relations (24) and (10), respectively, with allowance for the signs that determine the direction of motion of the reduced velocities of the phases.

The proposed relations of the overall model of drift for both ascending, Eq. (17), and descending, Eq. (32), motion of the phases are valid for static characteristics of flow. In dynamic calculations, the transition from one direction of motion of the coolant to the other can be achieved in a quasistatic approximation by using the relaxation equation

$$\frac{dV_{vj}}{dt} = \frac{1}{\tau}\left(V_{vj}^* - V_{vj}\right), \tag{33}$$

where

$$V_{vj}^* = \begin{cases} V_{vj}^{asc} & \text{when} \quad \rho w \ge 0, \\ V_{vj}^{des} & \text{when} \quad \rho w < 0. \end{cases}$$

In the first approximation the time constant τ can be taken to be $\tau = 1$ sec.

Thus, Eqs. (17), (32), and (33) describe the change in the drift velocity for different regimes and directions of motion of a two-phase coolant and can be used in dynamic calculations of reactor programs.

NOTATION

j, mixture velocity; j_v, j_{liq}, reduced velocities of vapor and liquid; ρw, mass velocity; $V_{vj,1}$, $V_{vj,2}$, $V_{vj,3,4}$, $V_{vj,5}$, drift velocities in the bubble, slug, annular, and falling film modes of flow, respectively; ρ_v, ρ_{liq}, densities of vapor and liquid; $\Delta\rho = \rho_{liq} - \rho_v$; g, free fall acceleration; σ, surface tension coefficient; ν, μ, kinematic and dynamic viscosities; φ, void fraction; D, $\overline{R}$, diameter and relative radius of a tube; $L = \Pi/2$, characteristic linear dimension; Π, channel perimeter; d_{eq}, equivalent diameter; $d_{f.el}$, diameter of a fuel element; a, b, small and large sides of a rectangular channel; n, number of fuel elements; $Fr_{liq} = j_{liq}/[g\Delta\rho L/\rho_{liq}]^{1/2}$, Froude number; $Bo = L/[\sigma/g\Delta\rho]^{1/2}$, Bond number; $N_\mu = \mu_{liq}/[\rho_{liq}\sigma\sqrt{\sigma/g\Delta\rho}]^{1/2}$; K_1, form factor of the channel in Eq. (12); C_0, C_{01}, C_{02}, C_{03}, C_{04}, distribution parameters determined from relations (2), (3), (4), (18), (19), (26), respectively; b, b_1, coefficients in relations (17) and (32). Subscripts and superscripts: v, vapor; liq, liquid; b, boundary; f.el, fuel element; baf, baffle plate; ass, rod assembly; in, inner; out, outer; rec, rectangular; ann, annular; t, tube; asc, ascending; des, descending; 1, 2, 3, 4, 5, bubble, slug, frothing, annular, and falling film regimes of flow, respectively.

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