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A PROCEDURE FOR CALCULATING THE CHARACTERISTICS OF A DISPERSED PHASE IN A MIST FLOW ON REWETTING

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The mechanisms involved in the formation of a range of droplets over a nonwetted region in a reflooded preliminarily heated channel are considered. A scheme is suggested for determining the droplet size.

Investigation of thermohydraulic processes in the case of reflooding a preliminarily warmed heat-liberating channel is involved in the solution of the problem of heat removal from power engineering equipment in emergency situations with the loss of a heat carrier. It is characteristic that in contrast to the range of parameters typical of normal functioning, the pressure and mass flow rate under the conditions considered are comparatively low ($P = 0.1$-0.5 MPa; $\rho w = 10$-150 kg/(m^2·sec)), and the start of the postcritical zone can be displaced to the negative relative enthalpy region because of the high subcooling of the emergency coolant below its saturation temperature. The main regime, which is of interest for estimating the temperature state of fuel elements, is the heat transfer in the nonwetted zone from an overheated surface to a dispersed mist flow. In this case, the droplet size, which governs the interphase heat transfer and the heat exchange between the wall and the droplets depositing on it, is an important parameter for describing the thermal hydraulics of reflooding.

The characteristic regimes of the heat transfer taking place on reflooding were considered, e.g., in [1]. At low flow rates of cooling water or in the cases where the rewetting front advances appreciably with respect to the test section entrance, a process is realized that is akin to the crisis with film drying, with the dispersed flow starting directly behind the wetting front. In the case of high water subcooling, the mist flow in the zone of the front in the nonwetted region is preceded by a reversed-annular regime. Here one can observe large liquid aggregates that separate from the liquid core and gradually disintegrate into smaller drops. It is clear that after reflooding the droplet size can vary within a wide range, which considerably hinders the development of a single technique for determining the dispersed phase characteristics for calculating the thermohydraulic processes under such conditions. For determining the droplet size the literature suggests different relations derived as a result of the analysis and correlation of the data obtained in a stationary experiment on postdryout heat transfer, where the range of droplets is being formed due to separation of the liquid from the perturbed film surface in the mist-annular mode in the subcritical region. The application of these correlations is justifiable to a certain degree for regimes with a high balanced vapor content in the zone of the front (for reflooding conditions when $X_b \geq 0.1$). However, for subcooling regimes in the zone of the front the "postdryout" equations underestimate the droplet diameter as compared with the droplet size in the recommendations on reflooding in [2], where the droplet diameter at the beginning of the dispersed flow is assumed to be 1.5 mm. After reflooding the droplets have a rather large size, due to the specific character of the mechanism involved in the generation of droplets and to the small velocity of the carrier phase. The vapor is generated, superheated, and accelerated in the nonwetted zone, which results in both a decrease in the droplet size due to the heat from the vapor and the wall and in possible disintegration under the action of turbulent pulsations. In contrast to solid particles, the droplets entrained by the vapor undergo deformation, and internal motions arise in them. The development of these processes leads to the deformation and destruction of the droplets, i.e., to disintegration into smaller droplets [3]. The successive disintegration of droplets may also precede the beginning of

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the dispersed regime of film boiling and persist over the entire nonwetted region. The period of destruction is composed of a time close to the characteristic time of disintegration t_s and the period of natural oscillations τ_d [3]:

$$t_s = d/(w_v - w_l)(\rho_l - \rho_v)^{0,5};$$
$$\tau_d = 0{,}25\pi\left(\frac{\sigma}{\rho_l d^3} - 6{,}25\frac{\mu_l^2}{\rho_l^2 d^4}\right)^{-1/2}. \tag{1}$$

The estimation of the values of t_s and τ_d under reflooding conditions ($t_s \simeq 2$ msec and $\tau_d \simeq 3$ msec) has shown that the separation required for droplet destruction is much smaller than the extent of the nonwetted region.

Investigations of the forced pulsations of droplets in an acoustic field [4] have shown that an intense increase in the amplitude of the droplet surface oscillations and subsequent disintegration of the droplets take place when the exciting and natural frequencies approach one another. For a turbulent channel flow, use of the model of resonance disintegration was suggested in [5] for determining the droplet size, with the condition for droplet disintegration being the coincidence of the characteristic frequency of turbulent pulsations of the carrying medium f_T with the natural frequency of a droplet ($f_d = 1/\tau_d$):

$$f_T = f_d. \tag{2}$$

Analysis of the pulsational energy distribution over the frequencies indicates the presence of different scales of turbulent vortices. In this scheme the choice of the frequency of pulsations in the flow is decisive. The use of high frequencies corresponding to the turbulent energy dissipation interval [6]

$$f_T = \frac{2w_*}{D}\sqrt{\mathrm{Re}_v}, \tag{3}$$

in [5] gave adequate values for the droplet diameter in a highly dispersed flow. Our use of the model of resonance disintegration with characteristic scales within the "inertia interval" of the energy spectrum underestimated the droplet diameter under the conditions considered, where the droplets are rather large (see curve 4 in Fig. 1). In [7] for reflooding conditions a prevailing role was assumed for low-frequency oscillations corresponding to energy-intensive vortices in the frequency-energy spectrum of a turbulent flow

$$f_T = 20w_*/D. \tag{4}$$

Considering Eqs. (1), (2), (4) and the inequality

$$6{,}25\mu_l^2/(\rho_l d^2)^2 \ll \sigma/(\rho_l d^3) \tag{5}$$

we may write

$$d = \left(\frac{0{,}04\sigma D^2}{\pi^2\rho_l w_*}\right)^{1/3} \tag{6}$$

or, after several simple transformations,

$$\frac{d}{D} = 0{,}464\mathrm{We}^{-1/3}\mathrm{Re}^{1/12}\left(\frac{\rho_v}{\rho_l}\right)^{1/3}. \tag{7}$$

As a rule, the aforegoing refers to a turbulent gas flow. At the same time, for the region of the start of the dispersed mode, a laminar vapor flow is possible. Then, in the physical sense, the frequency of the energy-intensive pulsations changes to the natural frequency of the flow, obtained when analyzing the equation for the disturbance propagation $f_L = 4w_*/D$; i.e., in a laminar flow the characteristic length scale is equal to $D/4$ as against $D/20$ in a turbulent flow. The simple scheme of determining the droplet diameter from the resonance disintegration model has the form

$$\frac{d^{res}}{D} = 0{,}464(5 - 4\varkappa)^{2/3}\mathrm{We}^{-1/3}\mathrm{Re}^{1/12}\left(\frac{\rho_v}{\rho_l}\right)^{1/3}, \tag{8}$$

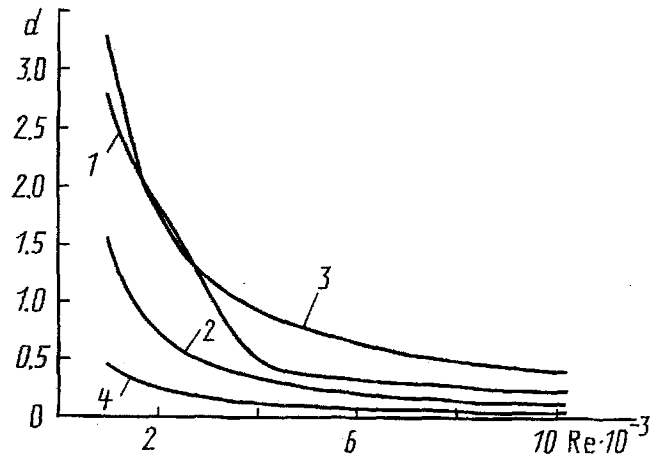

Fig. 1. Dimensions of droplets vs the Reynolds number based on the vapor velocity: 1) from the present model of resonance disintegration (8); 2) from Eq. (9); 3) from Eq. (10); 4) from the Zudin-Yagov model [5]. d, mm.

where

$$\varkappa = \begin{cases} 0, \text{ when } \mathrm{Re} < \mathrm{Re}_1 = 2300, \\ (\mathrm{Re} - \mathrm{Re}_1)/(\mathrm{Re}_2 - \mathrm{Re}_1), \text{ when } \mathrm{Re}_1 \leqslant \mathrm{Re} \leqslant \mathrm{Re}_2, \\ 1, \text{ when } \mathrm{Re} > \mathrm{Re}_2 = 4000. \end{cases}$$

The dependences of the droplet diameter on the Reynolds number (based on the carrier phase parameters) obtained from the resonance disintegration model and also from familiar semi-empirical equations (9) and (10) for the droplet size in the postdryout region of a channel with a hydraulic diameter of 10 mm are presented in Fig. 1.

The equation

$$\frac{d}{D} = 3{,}8\,\mathrm{We}^{-0,6}\,\mathrm{Re}^{0,1}\left(\frac{\rho_v}{\rho_l}\right)^{1/3} \tag{9}$$

has been recommended for calculating the droplet diameter in the section with the crisis of film drying [3].

The equation

$$\frac{d}{D} = 0{,}105\,\mathrm{We}^{-0,5}\,\mathrm{Re}^{0,1} \tag{10}$$

was obtained under the conditions of a highly dispersed flow, which characterizes the traditional regime of postdryout heat transfer [8]. At the same time, in a number of computational programs simulating thermohydraulic processes this equation is used for determining the size of droplets also under reflooding conditions. As is seen from Fig. 1, the droplet diameters determined from the resonance disintegration model (8), applied in the present work, and from Eq. (10) are close in value.

The change in the droplet diameter due to vapor-droplet and wall-droplet heat exchange implies the following scheme for calculating the mean-mass diameter of a droplet in the simulation of reflooding:

$$d = \min(d^{res},\ d^{vap}), \tag{11}$$

where d^{vap} is determined from the dynamics of droplet evaporation [2]:

$$d_{i+1}^{vap} = d_i + \int\limits_{\Delta = Z_{i\mp 1} Z_i} -\left(\frac{2q_{v-d}}{(h_v - h_l)\,\rho_l w_l} + \frac{4q_{w-d}d}{3\,(h_v - h_l)\,\rho_l w_l D\,(1-\varphi)}\right) dZ. \tag{12}$$

The value of d^{vap} for the start of the dispersed regime can be determined from Eq. (9). Thus, the droplet has the size most stable in the given section. It is determined with account for two different mechanisms involved in the interaction of the droplet with the flow.

In conclusion, we note that along with the mean-mass diameter $\bar{d}_1$, in the calculation of the vapor-droplet and wall-droplet heat exchange the surface-average diameter $\bar{d}_2$ is used, whereas for determining the number of droplets in the flow the volume-average diameter $\bar{d}_3$ is used. These quantities depend on the range of the size-distribution of the droplets $\eta(d)$:

$$\bar{d}_{(k)} = \left(\frac{\int_0^\infty d^k \eta(d)\, \alpha d}{\int_0^\infty \eta(d)\, \alpha d} \right)^{1/k}, \tag{13}$$

where k = 1, 2, 3 correspond to $\bar{d}_1$, $\bar{d}_2$, and $\bar{d}_3$.

Experimental investigations [9, 10] by visual observations under conditions close to reflooding showed the applicability of the Cumo range [11]

$$\eta(d) = \frac{d}{d_*^2} \exp\left(-\frac{d}{d_*}\right), \tag{14}$$

where d_* is the most probable droplet size. Then, it is easy to obtain that $d_1 = 2d_*$; $d_2 = 2.45d_*$; $d_3 = 4.9d_*$.

The verification of the models that describe separate mechanisms of heat and mass transfer under the conditions of thermally and mechanically nonequilibrium two-phase flow requires experimental data on local characteristics of the flow such as the vapor velocity, the relative velocity, the droplet diameter, and vapor superheating. At the present time the number of works dealing with reflooding conditions are very limited. For experiment No. 32114 of the series FLECHT [12, 13] (hydraulic diameter 11.78 mm, pressure 0.276 MPa, flow rate 25 kg/(m^2·sec)) the dispersed flow parameters were estimated in a section 0.91 m from the entrance at the time when the rewetting front was located at 0.18 m ($X_{b,f} = 0.015$). A quasi-stationary technique was employed for calculating the flow rate downstream of the front [1]. Using available data on the front velocity, this technique gives the value 0.265 m/sec for the mass vapor content and 8.6 m/sec for the vapor velocity. The droplet diameters determined from the recommended critical Weber numbers lie within the range from 7 to 12 mm. The measurement of the droplet size in the section considered gives a double-humped spectrum, and the size of large droplets varies from 0.2 to 3.3 mm. The diameter of the droplets determined from the resonance disintegration model (8) gives the value 2.7 mm.

Another comparison of the predicted droplet diameters with the experimental data was carried out for experiments with flow visualization at the Aragon laboratory [10], where Freon-113 was used as the liquid phase. For two experiments (Nos. 224 and 713) presented in [10], where nitrogen and helium were used as the gas phase, the arithmetic mean diameter of the droplets $\bar{d}_1$ is 1.5 and 1.0 mm, respectively. The maximum droplet diameters are 2.75 mm (experiment No. 224) and 1.95 mm (experiment No. 713), whereas calculation by the technique (8) gives 2.46 and 1.67 mm, respectively, which, as is seen, agrees quite satisfactorily with the data of observations.

NOTATION

P, pressure; ρw, mass flow rate; ρ, density; σ, surface tension coefficient; μ, dynamic viscosity coefficient; h, enthalpy; φ, volumetric vapor content; d, droplet diameter; Z, coordinates; D, hydraulic diameter of the channel; w, velocity; w_*, dynamic velocity, $w_* = w_v\sqrt{\xi/8}$; ξ, coefficient of resistance on the wall, $\xi = 0.316\mathrm{Re}^{-1/4}$; $\mathrm{We} = \rho w^2 D/\sigma$; $\mathrm{Re} = \rho w D/\mu$; $q_{v\text{-}d}$, heat flux from the vapor to the droplet; $q_{w\text{-}d}$, heat flux from the wall to the droplet. Subscripts: d, droplet characteristic. w, wall characteristic; v, vapor characteristic; l, liquid characteristic; i, index of the discrete analog unit; $\pi = 3.14159$.

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