METHOD OF CALCULATING THE HYDRAULIC RESISTANCE IN VAPOR-GENERATING TUBES AT LOW SPECIFIC HEAT FLUX

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The distribution of φ along the tube, and the distribution of friction and acceleration losses, are evaluated from the known distribution of α values in the boiling of liquids in tubes under conditions where the process of vapor generation has no effect on the intensity of heat transfer.

It is known that the intensity of heat transfer during boiling under conditions of directed motion of a liquid depends on the ratio between the rate of vaporization $q/r\gamma''$ and the velocity of forced motion of the liquid w [1]. The influence of mass transfer due to the process of vaporization on the intensity of heat transfer to the boiling liquid is evaluated by the parameter $\mathrm{Kw} = (q/r\gamma'')/w$.

For each liquid there exists a minimum value of $\mathrm{Kw} = \mathrm{Kw}_{\min}$ at which the influence of vaporization on the intensity of heat transfer cases. For stream volume vapor content values close to zero, the value of $\mathrm{Kw}_{\min}$ is found from the condition

$$\left(\frac{q}{r\gamma'' w}\right)_{\min}\left(\frac{\gamma''}{\gamma'}\right)^{1.45}\left(\frac{r}{C_pT_s}\right)^{0.33} = 0.4\cdot 10^{-5}. \quad (1)$$

If

$$\mathrm{Kw} \leqslant \mathrm{Kw}_{\min}, \quad (2)$$

then, for vapor content close to zero, $\alpha = \alpha_{\mathrm{conv}}$ [2]. The same also applies to surface boiling [3]. In this region of the regime parameters the increase in heat transfer coefficient in boiling over its value in convective heat transfer in a single-phase medium may possibly be due only to the vapor content resulting from increase of the true velocity of motion of both phases.

If we adopt this point of view, it is then possible to construct a curve of distribution of true vapor content from the known distribution of local values of the heat transfer coefficient along the vapor-generating tube. In fact, in single-phase flow under turbulent conditions the heat transfer coefficient is proportional to fluid velocity to the power 0.8. Therefore, from the value of the heat transfer coefficient $\alpha_{\mathrm{conv}\,\varphi}$ at some true volume vapor content φ, we can determine the mean true velocity of motion of the liquid phase w':

$$\alpha_{\mathrm{conv}\varphi}/\alpha_{\mathrm{conv}} = (w'/w_0)^{0.8}. \quad (3)$$

The mean true velocity of the liquid w' is determined in terms of its reduced velocity w_0',

$$w' = w_0'/(1-\varphi), \quad (4)$$

while the circulation velocity is connected with the reduced phase velocities w_0' and w_0'' by the relation

$$w_0 = w_0' + w_0''(\gamma''/\gamma'). \quad (5)$$

Thus

$$w' = \frac{w_0 - w_0''\gamma''/\gamma'}{1-\varphi}. \quad (6)$$

Substituting the value of w' into (3), we obtain

$$\frac{\alpha_{\mathrm{conv}\varphi}}{\alpha_{\mathrm{conv}}} = \left[\frac{w_0 - w_0''\gamma''/\gamma'}{(1-\varphi)w_0}\right]^{0.8}, \quad (7)$$

whence

$$\varphi = 1 - \frac{w_0 - w_0''\gamma''/\gamma'}{w_0}\left(\frac{\alpha_{\mathrm{conv}}}{\alpha_{\mathrm{conv}\varphi}}\right)^{1.25}. \quad (8)$$

For low values, when $\gamma''/\gamma \ll 1$, (8) may be transformed to

$$\varphi = 1 - (\alpha_{\mathrm{conv}}/\alpha_{\mathrm{conv}\varphi})^{1.25}. \quad (9)$$

The acceleration resistance in the flow of a two-phase stream is determined from the formula [4]

$$\Delta P_{\mathrm{acc}} = \left[\frac{\gamma w_0'^2}{g}\,\frac{\varphi + (1-\varphi)\gamma'' w_0''^2/\gamma' w_0'^2}{\varphi - \varphi^2}\right]_2 - \left[\frac{\gamma w_0'^2}{g}\,\frac{\varphi + (1-\varphi)\gamma'' w_0''^2/\gamma' w_0'^2}{\varphi - \varphi^2}\right]_1. \quad (10)$$

For zero initial vapor content and conditions of surface boiling, when unheated liquid enters the tube, w_0'' and φ are equal to zero in the initial section. Then (10) reduces to the form

$$\Delta P_{\mathrm{acc}} = \frac{\gamma w_0^2}{g}\left[\frac{\varphi + (1-\varphi)\gamma'' w_0''^2/\gamma' w_0'^2}{\varphi - \varphi^2} - 1\right]. \quad (11)$$

In boiling under low pressure conditions, the losses in accelerating the vapor phase do not exceed 10% of the losses in accelerating the liquid, even with an appreciable true vapor content at the exit, owing to the small mass of the vapor phase. If the losses in accelerating the vapor phase are neglected, then from (11) we obtain

$$\Delta P_{\mathrm{acc}} = \frac{\gamma w_0^2}{g}\,\frac{\varphi}{1-\varphi}. \quad (12)$$

In adiabatic flow of a two-phase stream, the friction losses in the case of a turbulent regime of motion of the liquid film may be calculated from the following formula [4]:

Characteristics of the Steam-Generating Tubes

q, kJ/m²·sec	ω, m/sec	P_{in}, kN/m²	T_{in}, °K	ΔP_{in}, kN/m²	ΔP_{out}, kN/m²	ΔP_{fr}, kN/m²	ΔP_{acc}, kN/m²	ΔP_{theor}, kN/m²	ΔP_{exp}, kN/m²
236.1	1.2	160.25	376.87	0.127	1.425	2.423	2.383	6.080	6.139
236.1	1.2	167.3	379.6	0.127	1.444	3.175	3.089	7.836	7.404
152.35	1.5	151.9	379.15	0.127	0.588	2.050	1.667	4.491	4.325
148.86	1.5	167.5	383.65	0.127	2.609	4.992	4.707	12.671	12.671
152.35	1.2	150.4	375.95	0.127	0.352	0.675	0.956	2.650	2.687
152.35	1.2	151.6	378.55	0.127	0.613	1.525	1.373	3.913	3.844
233.76	1.5	147.3	374.85	0.186	0.686	1.407	1.520	4.148	4.492
151.2	1.5	148.8	377.45	0.177	0.417	1.020	0.961	3.227	2.687
233.76	1.5	149.6	374.95	0.186	0.637	1.618	1.844	4.786	4.796
238.4	1.2	148.6	369.75	0.127	0.819	0.736	0.726	2.285	2.452
145.4	1.5	244.2	392.65	0.182	0.314	0.628	0.628	2.452	2.207
151.9	1.21	155.9	371.55	0.132	0.265	2.452	1.618	4.467	4.923

$$\Delta P_{fr}/\Delta P_0 = 1/(1-\varphi)^{2.3}. \tag{13}$$

It was shown in [4] that this function is not very sensitive to the regime of motion of the liquid film.

On the basis of (8), (11), and (13), we may establish directly the connection between the intensity of heat transfer and the hydraulic resistance due to friction and acceleration of the stream, if condition (2) is fulfilled.

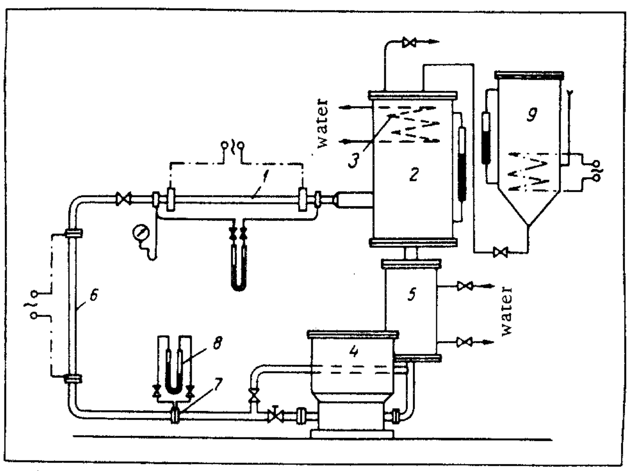

Fig. 1. Layout of the experimental rig.

An especially simple relation is obtained at low pressure. Then (9), (12), and (13) are valid, from which we obtain, by simple transformations

$$\Delta P_{fr}/\Delta P_0 = (\alpha_{conv\varphi}/\alpha_{conv})^{2.85}, \tag{14}$$

$$\Delta P_{fr} = \Delta P_0 (\alpha_{conv\varphi}/\alpha_{conv})^{2.85}, \tag{15}$$

$$\Delta P_{acc} = \frac{\gamma w_0^2}{g}\left[\left(\frac{\alpha_{conv\varphi}}{\alpha_{conv}}\right)^{1.25} - 1\right]. \tag{16}$$

From (8), (11), and (13), for conditions satisfying (2), we may derive the distribution of φ, ΔP_{fr}, and ΔP_{acc}, if local values of the ratio $\alpha_{conv\,\varphi}/\alpha_{conv}$ are known. At low pressure, for condition (2), the distribution of φ and of pressures along the tube are obtained from (9), (14), and (16).

We carried out an investigation of hydraulic resistance under conditions of surface and developed boiling of water at pressures of 147 and 245 kN/m².

The tests were conducted on a rig (Fig. 1) in the form of a closed circuit consisting of an experimental test section 1, a separator 2 with condenser 3, circulating pump 4, cooler 5, and heater 6. The cooler and the heater were used to control the water temperature at the inlet to the test section. The pressure in the system was created with the aid of a supplementary vapor generator 9 with an electric heater.

The rate of circulation of the liquid was controlled by a valve on the pump bypass line. The mass flow rate was measured with a twin standard orifice 7, which was previously calibrated. The pressure drop over the orifice was measured by a differential manometer 8, filled with dichloroethane.

The separator had a blow-off valve for discharge of air in degassing of the liquid. The experimental section took the form of a horizontal brass tube, heated by a low-voltage ac current. The inner diameter of the tube was 0.00897 m, the wall thickness 0.0005 m, and the length of the heated section 0.522 m. The distance between pressure taps was 0.670 m. The length of the inlet and exit unheated sections was about 0.070 m. The hydrodynamic stabilizing section ahead of the heated section of the tube had a length of roughly 100 diameters.

The pressure drop in the experimental section was measured on a differential manometer filled with tetrabromoethane ($\gamma = 2.96$ g/cm³), and the absolute pressure at the tube entrance was measured with a standard manometer. To pick off pressure at the entrance and exit of the tube, holes of diameter 0.0009 m (for around the section) were drilled, and interconnected by a ring-shaped manifold.

Copper-constantan thermocouples were used to measure the stream temperature at the entrance and exit, and also the temperatures of the tube wall in the heated section (at thirty points). Prior calibration tests with isothermal flow showed that the experimental tube may be regarded as absolutely smooth.

Test values of the resistance coefficient over the whole range of Re numbers (Re up to 10^5) showed good agreement with values calculated according to the Blasius formula, the deviation not exceeding ± 3%.

Calibration tests were also run to establish the influence of heat flux on hydraulic resistance in a

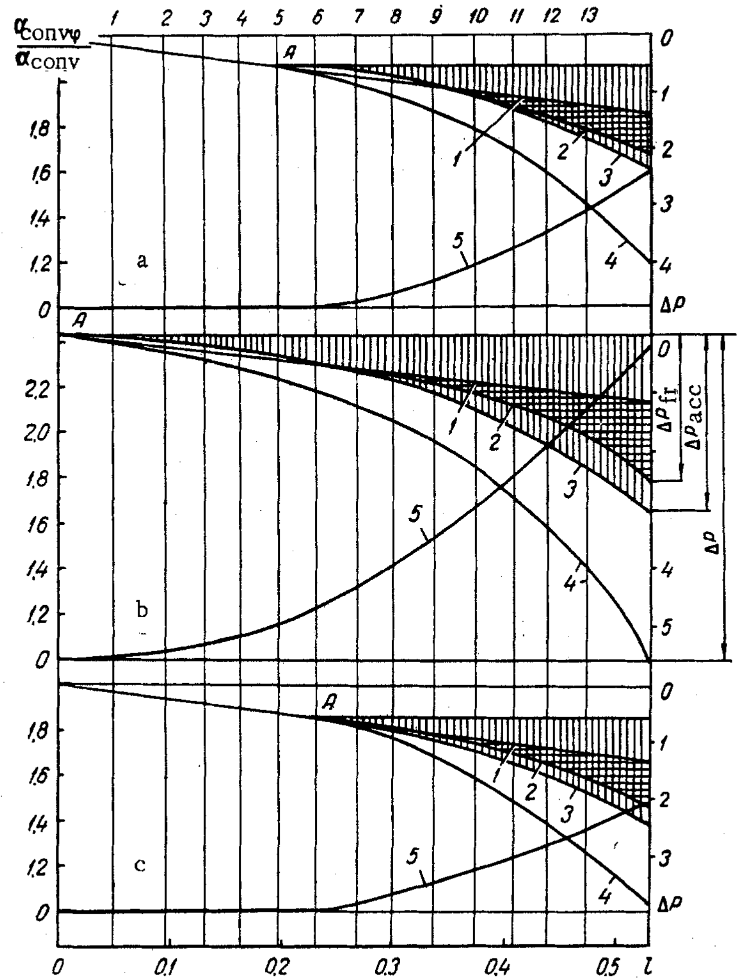

Fig. 2. Distribution of $\alpha_{conv\varphi}/\alpha_{conv}$, pressure, and hydraulic losses due to friction and acceleration along the vapor-generating tube: 1) pressure losses in isothermal flow; 2) friction pressure losses in boiling; 3) pressure losses due to flow acceleration in boiling; 4) pressure distribution; 5) distribution of $\alpha_{conv\varphi}/\alpha_{conv}$ (according to test data).

single-phase medium. The results showed good agreement with the known relation

$$\xi_h = \xi_0 (\mu_w/\mu_l)^{0.14}. \qquad (17)$$

A series of principal tests was carried out. In each series the specific heat flux, and the velocity and pressure at the tube entrance, were kept constant, while the liquid temperature at the tube entrance was varied. The series began with tests without boiling, and ended with tests in which the liquid was in a saturated state at the entrance.

The distribution of pressure loss along the tube due to friction and acceleration was checked against the distribution of $\alpha_{\text{conv}\varphi}/\alpha_{\text{conv}}$. For this purpose, the total length of the tube was divided into sections of length 0.05 m, and the friction resistance of each section was calculated according to (15) from the mean local value of $\alpha_{\text{conv}\varphi}/\alpha_{\text{conv}}$. The acceleration losses were determined from (16). The resistance in the unheated entrance section was determined from the usual formula for single-phase flow. In all of the tests, the liquid temperature at the exit of the heated section was equal to the saturation temperature, and vapor condensation was not observed. Therefore, at the exit section the acceleration resistance was taken to be zero, while the friction resistance was determined from (15) with the value of $\alpha_{\text{conv}\varphi}/\alpha_{\text{conv}}$ at the tube exit, i.e., from the value of φ at the exit of the heated section of the tube.

The test results are shown graphically in Fig. 2 for the following conditions: a) $q = 233.76$ kJ/m^2 · sec, $w = 1.5$ m/sec, $P_{in} = 147.3$ kN/m^2, $T_{in} = 374.85°$ K (Fig. 2a); b) $q = 236.1$, $w = 1.2$, $P_{in} = 167.3$, $T_{in} = 379°$ K (Fig. 2b); c) $q = 152.35$, $w = 1.5$, $P_{in} = 151.9$, $T_{in} = 379.15°$ K (Fig. 2c).

The locations of the thermocouples measuring the tube wall temperature in the heated section are indicated in Fig. 2 by the numbers 1–13.

The curves are drawn to begin at point A, which corresponds to the start of increased heat transfer. The horizontally shaded area corresponds to increased pressure losses from friction due to vaporization. The vertically shaded area indicates the growth of pressure losses due to flow acceleration. The total pressure drop in the tube (curve 4) was determined by summing the friction and acceleration losses.

The results of the calculations for a number of tests are shown in the table.

It may be seen from the table that the calculated pressure drop values differ from those measured by no more than 10%.

NOTATION

q—specific heat flux; w—velocity of forced motion of liquid; w_0—circulation velocity; w'—mean true velocity of motion of liquid phase; w_0' and w_0''—reduced velocities of motion of liquid and vapor phases, respectively; T_s—saturation temperature; T_{in}—inlet temperature; P_{in}—inlet pressure; ΔP_0—pressure drop for isothermal liquid flow; ΔP_{in}—pressure drop over unheated section at tube entrance; ΔP_{out}—pressure drop over outlet unheated section; ΔP_{acc}—pressure drop due to flow acceleration; ΔP_{fr}—pressure drop due to friction with $\varphi \neq 0$; ΔP_{theor}—calculated pressure drop in test section; ΔP_{exp}—experimental pressure in test section; ξ_0 and ξ_h—resistance coefficients for isothermal flow and flow with heating; φ—true volume vapor content; α-heat transfer coefficient with boiling; α_{conv} and $\alpha_{\text{conv}\,\varphi}$—heat transfer coefficients in flow without boiling at $\varphi = 0$ and at $\varphi \neq 0$; Re—Reynolds number; r, C_p, γ, γ''—latent heat of vaporization, heat capacity, and density of liquid and vapor phases corresponding to the saturated state; μ_w and μ_l—dynamic viscosities at wall and liquid temperatures averaged over the length; l—length. Subscripts: 1—initial, 2—final sections.

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