CALCULATION OF THE CRITICAL VELOCITY OF A STEAM-WATER MIXTURE CORRESPONDING TO FALL-OFF IN HEAT TRANSFER

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A formula is given for the critical velocity of a steam-water mixture corresponding to deterioration in heat transfer. A method is recommended for calculating the steam mass content at which heat transfer begins to fall off.

In the operation of high-pressure steam generating plants deterioration of heat transfer may occur as a result of disturbance of the stability of nucleate boiling on the steam-generating heating surface. The fall-off in heat transfer in a flow of steam-water mixture was described in [1-3]. It was observed, in tests at a pressure of 167.0×10^5 N/m^2 [1], that fall-off in heat transfer at large steam contents depends on the velocity and heat flux. The conditions for fall-off in heat transfer in a flow of steam-water mixture in vertical tubes were investigated in [4], where tests were carried out on a tube of 8 mm diam. at pressures from 4.9×10^5 to 206.0×10^5 N/m^2. The mass velocity was varied from 100 to 13 200 kg/m^2 · sec, and the heat flux from 98.5×10^3 to 3.88×10^6 W/m^2.

Fall-off in heat transfer is often observed as a result of the stability of the flow of liquid being disturbed when the steam reaches a certain critical velocity [4-7]. A study of the stability conditions of the liquid-gas system must take into account the interaction of forces of inertia, gravity, surface tension, and friction. The following formula for determining the stability conditions of the liquid-gas system was proposed in [7]:

$$\frac{w''_{\mathrm{cr}}\sqrt{\gamma''}}{[g^2\sigma(\gamma'-\gamma'')]^{1/4}} = \Phi\left(\mathrm{Re}';\ \mathrm{Ga};\ \mathrm{Re}'';\ \mathrm{We};\ \frac{\gamma'}{\gamma''};\ \frac{l_1}{l}\right). \tag{1}$$

Since, under critical conditions $\mathrm{Re}'' = w''_{\mathrm{cr}} l/\nu''$, it is recommended to use, in place of (1), the equation

$$\frac{w''_{\mathrm{cr}}\sqrt{\gamma''}}{[g^2\sigma(\gamma'-\gamma'')]^{1/4}} = \Phi_1\left(\mathrm{Re}';\ \mathrm{Ga};\ \mathrm{We};\ \frac{\gamma'}{\gamma''};\ \frac{\nu''}{\nu'};\ \frac{l_1}{l}\right). \tag{2}$$

In (1) and (2) the criterion to be determined is formed as the square root of the ratio of the dynamic head and the scale of the gravity force, i.e., in essence,

$$w''_{\mathrm{cr}}\sqrt{\gamma''}/[g^2\sigma(\gamma'-\gamma'')]^{1/4} = \mathrm{Fr}^{1/2}. \tag{3}$$

Criterion (3) is used, in somewhat modified form, to calculate the critical heat flux for bulk boiling and boiling in tubes at small circulation velocities and steam contents [5, 6, 8].

Calculation of the true steam velocity w" is difficult. There is, moreover, a unique relationship [9, 10] between the true steam velocity and the flow velocity of the steam-water mixture w_m. In the range of parameters in question, the true steam velocity, according to the data of [10], varies almost linearly with the mass flow velocity of the steam-water mixture. This single-valued relation allows us to take the latter as the critical parameter to be determined in (3).

The influence of the ratio of the inertia forces to the viscous forces in the liquid is expressed by the Re number:

$$\mathrm{Re}' = Q_m/\nu'.$$

Both the true and the reduced velocities of the liquid and vapor phases are dependent variables and do not enter into the uniqueness condition. The circulation velocity, which characterizes the make-up of the liquid phase, is an independent variable and may determine the hydrodynamics of the liquid. It is therefore desirable to represent the hydrodynamics of the liquid phase by the Re number based on the circulation velocity:

$$\mathrm{Re} = w_0 d/\nu'. \tag{4}$$

In order to characterize the regime of both phases, the simplex ν''/ν'[6] should be included in the analysis.

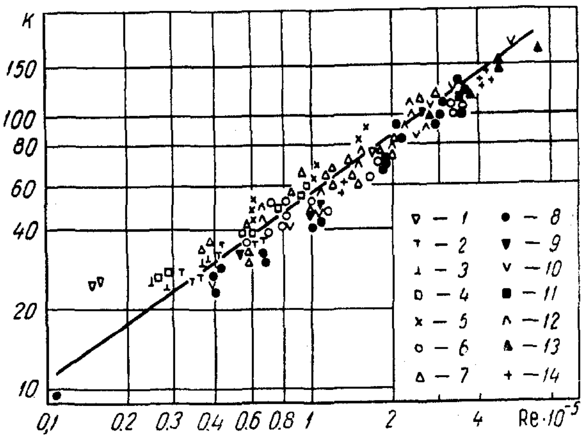

Fig. 1. The complex K as a function of Re: 1-11) for d = 8 mm, pressures from $4.9 \cdot 10^5$ to $208 \cdot 10^5$ N/m^2; 12, 13) 4 mm, $49 \cdot 10^5$ and $147 \cdot 10^5$ N/m^2; 14) 32.2 mm, $147 \cdot 10^5$ N/m^2.

Besides the parameters cited, there are also included the Weber number $We = \sigma/(\gamma' - \gamma'')\,d^2$, which determines the ratio of gravity to surface tension forces, and the parameter $1 - \gamma''/\gamma'$, which represents the relative density of the phases.

The results of processing the experimental data of [4] for tubes of three diameters are given in Fig. 1 in the form of a relation between

$$K = \frac{w_m^{cr}\sqrt{\gamma''}}{[g^2\sigma(\gamma' - \gamma'')]^{1/4}}\, We^{-0.4}\left(\frac{\nu''}{\nu'}\right)^{-0.5}\left(1 - \frac{\gamma''}{\gamma'}\right)^{3}$$

and Re. The majority of the experimental points are well grouped around the straight line.

To calculate the critical velocity w_m^{cr} at which deterioration in heat transfer occurs in an ascending flow of steam-water mixture in the range of parameters investigated, the following empirical formula is recommended:

$$\frac{w_m^{cr}\sqrt{\gamma''}}{[g^2\sigma(\gamma' - \gamma'')]^{1/4}} = 0.0155\, Re^{0.7}\, We^{0.4}\left(\frac{\nu''}{\nu'}\right)^{0.5}\left(1 - \frac{\gamma''}{\gamma'}\right)^{-3}. \quad (5)$$

As may be seen from Fig. 2, the scatter of the experimental points is ±25%.

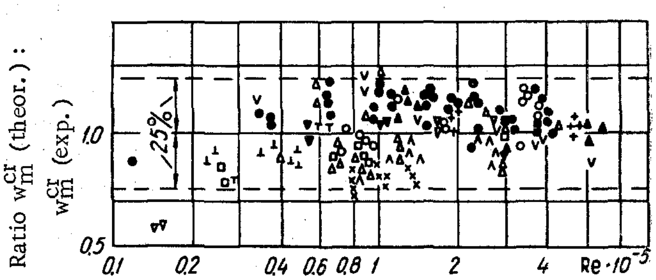

Fig. 2. Comparison of experimental data with the theoretical formula obtained (for 1-14 see Fig. 1).

It is known that

$$w_{cr}'' = w_0\,[1 + x(\gamma'/\gamma'' - 1)]. \quad (6)$$

For a given circulation velocity, Eq. (5) may be used, in conjunction with (6), to calculate the mass steam content x_d at which deterioration of heat transfer sets in for an ascending flow of steam-water mixture. Here the accuracy in calculating x_d is ±25%.

NOTATION

w''_{cr} – critical steam velocity; w_m^{cr} – critical velocity of steam-water mixture; w_m – velocity of steam-water mixture; w_0 – circulation velocity; γ' and γ'' – specific weight of liquid and vapor on saturation line; σ – surface tension; l_1 and l – linear dimensions of system; ν' and ν'' – kinematic viscosity of liquid and vapor; d – tube diameter; x – mass steam content; x_d – mass steam content at which deterioration of heat transfer sets in; Q_m – volume flow rate per running meter of wetted perimeter; Re – Reynolds number; Ga – Galileo number; We – Weber number; Fr – Froude number.

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