We can obtain an expression for \( K \) by determining the reduced velocity of the steam \( W'' \) from Eq. (5)

\[
K = \left[ \frac{C}{1 + \left( \frac{\rho'}{\rho''} \right)^{1/4}} \right]^2 \left[ \frac{D \sqrt{g(\rho' - \rho'')}}{\sigma} \right]^{1/2}.
\]

(10)

Figure 3 shows the results of the analysis of the experimental data in terms of the criterion \( K \) as a function of the parameter \( D \sqrt{g(\rho' - \rho'')} / \sigma \). The computed curves, obtained using Eq. (10) taking into account (8), are indicated here as well.

In the pressure range from 0.5 to 8 MPa, relation (10) agrees quite well with the experimental data and is recommended for use with calculations of critical heat loads in vertical tubes with the lower end sealed.

**NOTATION**

\( W', W'' \), reduced velocities of water and steam; \( \rho', \rho'' \), density of water and steam; \( B \), diameter of the tube; \( g \), acceleration of gravity; \( Q \), total heat flux; \( r \), heat of evaporation; \( \sigma \), coefficient of surface tension.

**LITERATURE CITED**


**HYDRAULIC RESISTANCE FOR LIQUID FLOW WITH BOILING-UP IN A PARTIALLY HEATED CHANNEL**

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An approximate analytic solution is obtained to the problem of calculating the hydraulic resistance. The hydraulic characteristics are analyzed and the region for static instability is determined.

At the present time, heat removal systems with long channels are constructed in cryogenic technology. These systems are characterized by a relatively low heat flux density, which allows for heat removal in the single-phase (economizing) region with subsequent boiling-up of the liquid along the adiabatic (unheated) section of the channel. Thus, for example, the low-temperature state of the heat-absorbing shields of thermal vacuum chambers is maintained in this manner with the help of a natural circulation loop with an external boiling zone [1], as is the cooling of cryogenic condensation pumps and cryogenic electrical devices with forced circulation of liquid nitrogen and helium in parallel channels.

Boiling-up of a liquid in this case is understood to be the process of evaporation caused by a decrease in pressure. References [3] and [3] examine primarily the boiling-up process as resulting from an increase in the flow rate due to a decrease in the channel cross section or a sudden change in pressure. In this case, the kinetic energy of the flow is low in comparison with the enthalpy, and for this reason, the change in the flow rate along the length of the channel can be neglected. However, the change in pressure along the channel,
caused by losses due to friction and decrease in the leveling component, is comparable to
the absolute pressure of the liquid and is accompanied by additional evaporation. The rela-
tively low rate at which the pressure changes along the length of the channel and the low
mass vapor content create favorable conditions for thermodynamic equilibrium. Under these
conditions, the problem can be formulated as follows.

A liquid, the enthalpy of which is known, enters into the vertical adiabatic channel
(Fig. 1). A heat flux, which can be assumed to be concentrated in a single section, is input
to the liquid in the initial section. The absolute pressure of the liquid decreases in pro-
portion to its motion due to losses to friction and changes in the leveling component. For
some cross section, at a distance \( l \) from the outlet, the liquid begins to boil and above
this section there is a two-phase flow, the vapor content of which increases due a decrease
in pressure. It is necessary to determine the hydraulic resistance as a function of the
flow rate, assuming that the pressure at the channel outlet is known.

Let us make the following assumptions: the flow of the liquid is uniform; the two-phase
flow can be assumed to be homogeneous with thermodynamic equilibrium between the liquid and
vapor phases; the liquid is incompressible; losses due to acceleration can be neglected; the
physical properties of the liquid and gas are constant; the vapor content at the outlet is
relatively low; the coefficient of friction does not depend on the flow rate.

We will first examine the section of the channel in which boiling-up occurs (\( L - l < z < L \)). Taking into account the details of the problem and the assumptions made above, we will
represent the equation of motion and energy for the adiabatic channel in the form

\[
\frac{dP}{dz} = \xi G^2 v_m + \frac{g}{v_m}; \quad \frac{d i_m}{dz} = 0,
\]

where

\[
\xi = \frac{k}{2d}; \quad n = \frac{\sigma}{\sigma'} - 1.
\]

In this case, it is useful to use the Clausius-Clapeyron equation for the equation of state:

\[
\frac{d P_s}{d T_s} = \frac{r}{T_s (\sigma' - \sigma')}. \tag{5}
\]

If Eq. (5) is written in a finite-difference form and we change over to the change in en-
thalpy, then we obtain

\[
i = a + b P_s, \tag{6}
\]

where

\[
a = i_2 - c_p T_{s2} \frac{\sigma' - \sigma'}{r} P_{s2}; \quad b = c_p T_{s2} \frac{\sigma' - \sigma'}{r}.
\]

The values of the coefficients \( a \) and \( b \) in (6) are determined only by the physical proper-
ties of the liquid at the outlet. In particular, for liquid nitrogen in the pressure range
0.1-0.3 MPa, the values of these coefficients can be taken as follows: \( a = 1.92 \times 10^6 \) J/kg, \( b = 0.1 \) J*m\(^2\)/kg*N, and for helium at pressures ranging from 0.1-0.2 MPa, \( a = 3.8 \times 10^6 \) J/kg and \( b = 5.9 \times 10^6 \) J*m\(^2\)/kg*N.

Since we are only considering the boiling region, taking into account thermodynamic
equilibrium, we have

\[
P = P_s. \tag{7}
\]

The system of equations (1)-(4), (6), and (7) is closed with respect to the variables
\( P, P_s, i_m, i, \) and \( x \). Using the boundary condition at the outlet, we obtain a solution in the
form

\[
\Delta P = P - P_2 = \frac{u - [(a^2 + k) \exp (-2 \xi G^2 \beta z) - k]^{1/2}}{\beta}, \tag{8}
\]