CONVECTIVE MASS TRANSFER IN THE EVAPORATIVE COOLING OF A STRONGLY HEATED SURFACE BY A VORTICAL TWO-PHASE FLOW

R. Z. Alimov

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This paper investigates mass transfer when a thin layer of water covering the internal surface of an externally heated, undiaphragmed, vortex tube evaporates into a vortical air flow in the case of high fluxes of the diffusing substance (water vapor).

If a liquid is sprayed in the form of small droplets into the entrance of a tube formed by a vortical flow of gas, centrifugal forces will throw the liquid onto the wall and it will be entrained by the flux towards the exit section, thus forming, in certain conditions, a continuous rotating film on the wall (Fig. 1).

A full description of the method of obtaining such films and the apparatuses for investigating heat and mass transfer from their surface into a vortical air flow was given in [1–4]. This paper, as distinct from [1–4], gives data relating to higher fluxes of the diffusing substance (water vapor) and to greater heat flux through the tube wall, since the water film was heated by the passage of an electric current through a nichrome ribbon closely wound on the tube over a thin layer of mica (Fig. 1).

This method of heating gives heat fluxes of up to $4 \cdot 10^5$ W/m^2 and mass fluxes of the diffusing (active) component of up to 500 kg/m^2 · hr, or 30 kmole/m^2 · hr, in tubes of small diameter (15.6 and 22.4 mm) and small relative length (up to 50 L/D).

The experimental data obtained when a continuous and stable film was formed over the whole inner surface of each investigated vortex tube with a prescribed geometric characteristic and relative length for each regime, characterized by particular values of the heat flux through the wall, flow rates of liquid and gas, and initial parameters, were used to plot curves of temperature of the evaporating liquid film against the tube length. Some of these curves are shown in Fig. 2.

These data can be used to determine the different components of the heat balance of the vortex tube. The heat balance can be written as follows:

$$Q_e = Q_{\text{mix}} + Q_D + Q_\alpha + Q_r + Q_L. \qquad (1)$$

The heat loss Q_L to the surroundings through the external insulation was determined from the results of preliminary calibration experiments by a method similar to that used in [5]. The heat Q_{mix} spent in heating the liquid was determined by calculation. In the first approximation, when the amount of evaporated liquid is unknown, the heat flow rate is assumed to be constant along the tube. In the subsequent approximations a more accurate calculation is made by sections, into which the whole length of the tube is divided, and an allowance is made for the change in liquid flow rate due to evaporation. The heat Q_r used up in heating the vapor-gas mixture by radiation was assumed to be negligible. The heat Q_α used up on convective heating of the mixture was determined by successive calculation for each section on the basis of the joint solution of the heat transfer and enthalpy equations. In the course of these calculations the increase in temperature of the mixture was simultaneously determined for each section and the temperature change along the tube was then determined for the known initial gas temperature. The coefficient of heat transfer from the film surface to the vortical air flow was determined by using the previously obtained relationships for pure heat transfer [3]. No correction for the effect of the concurrent and cocurrent flow of evaporating liquid was introduced owing to the lack of reliable information for this case [6–7]. A comparison of the measured and calculated temperatures of the vapor-gas mixture showed a difference of less than 5–10%, thus indicating the minor role of this correction in the investigated case. Figure 2 shows the calculated variation of temperature of the vapor-gas mixture along the tube for two regimes.

The heat Q_e produced by the electric heater was calculated by the usual method from the voltage drop and the current passing through the nichrome ribbon.

The described method provides a means of determining the heat Q_D spent on evaporation of the liquid, i. e., the parameter directly characterizing the mass transfer as the residual term in the heat balance of the tube.

The percentage distribution of heat among the different components in relation to the regime and section of the tube varied considerably. In most cases, however, the main fraction, up to 90% or more, consisted of heat transferred by evaporation.

The mass transfer coefficient β_p was calculated from the following relationship:

$$\beta_p = \frac{Q_D}{rF_w(P_{DF} - P_{Df})} = \frac{G_D}{F_w(P_{DF} - P_{Df})}. \qquad (2)$$

The mean value of β_p for the whole tube was determined by taking P_{DF} and P_{Df} as the mean integral values of the partial vapor pressure at the film surface and in the gas flow. The partial pressure at the film surface was taken equal to the saturated vapor pressure at the average liquid temperature over the thickness of the film, as indicated by the hot thermocouple junctions. The change in temperature over the thickness of the film, the flow of heat in an axial direction along the tube wall, and also the errors in the readings of the surface thermocouples due to the thermal re-

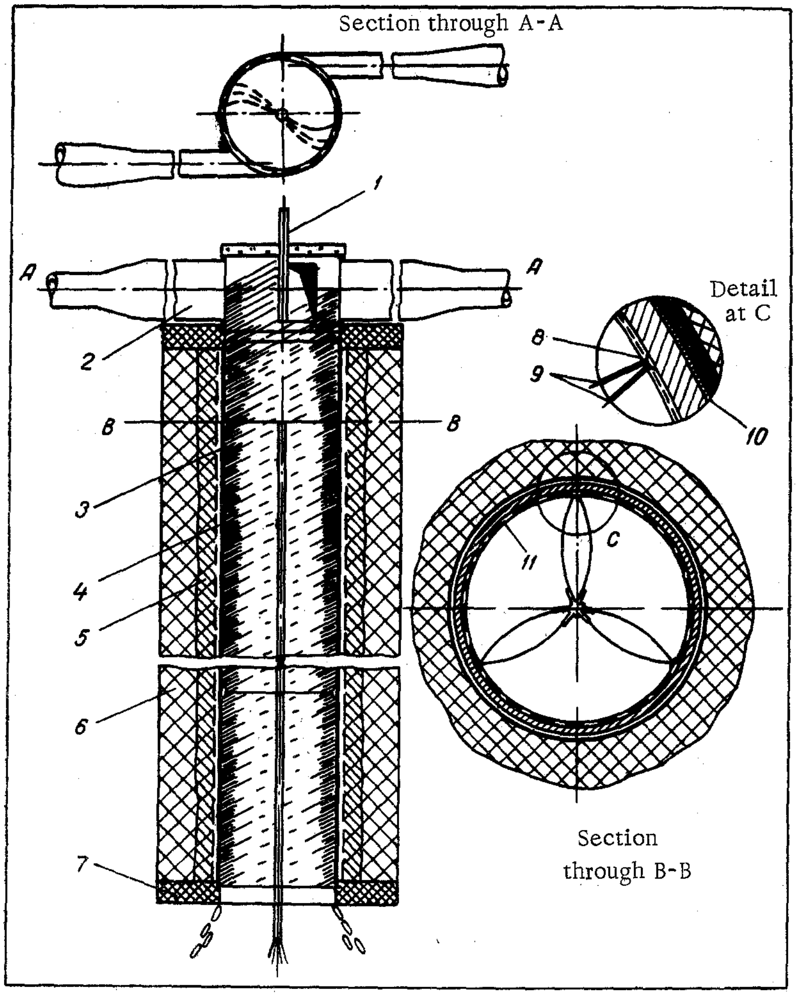

Fig. 1. Diagram of apparatus for investigating the evaporation of a liquid film in a vortical gas flow: 1) liquid sprayer; 2) air jet; 3) vortex tube; 4) nichrome ribbon; 5) refractory clay; 6) asbestos insulation; 7) asbestos cement plate; 8) hot junctions of thermocouples; 9) thermocouple electrodes; 10) mica layer; 11) liquid film.

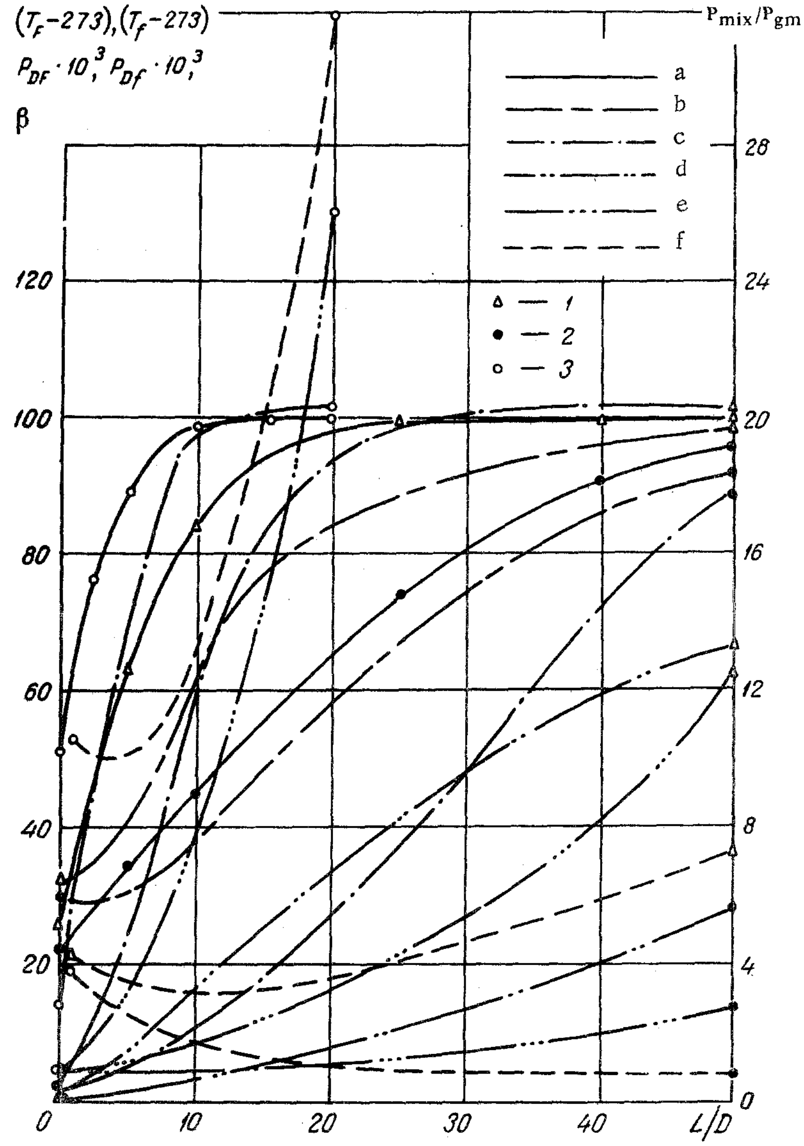

Fig. 2. Change in parameters of vortical two-phase flow T_F T_f, °K (a,b), P_{DF}, P_{Df}, N/m^2(c,d); P_{mix}/P_{gm}(e), $\beta = \beta_p \cdot 2 \cdot 10^{-4}$ (f) along tube: 1) φ = 22.4 mm, L/D = 50, $A_{h.t}$ = 0.4, G_l = 21 kg/hr, $Re_f = 2 \cdot 10^4$, $q = 1.5 \cdot 10^5$ W/m^2, T_{l0} = 297°K, T_{g0} = 305°K; 2) φ = 22.4 mm, L/D = 50, $A_{h.t}$ = 0.4, G_l = 21 kg/hr, $Re_f = 1.2 \cdot 10^4$, $q = 5 \cdot 10^4$ W/m^2, T_{l0} = 295°K, T_{g0} = 303°K; 3) φ = 15.6 mm, L/D = 20, $A_{h.t}$ = 2.5, G_l = 12 kg/hr, $Re_f = 6.5 \cdot 10^3$, $q = 4 \cdot 10^5$ W/m^2, T_{l0} = 293°K, T_{g0} = 298°K.

sistance of the zone of contact and removal of heat due to the heat conduction of the electrodes were neglected in view of their smallness in the investigated conditions (the films had an initial thickness of not more than 0.3–0.4 mm; under the action of centrifugal forces and the high tangential stresses on the free surface they were vigorously mixed in a radial direction; owing to the high rate of heat and mass transfer the film temperature did not differ much from the temperature of the air flow, and so on).

The partial vapor pressure P_{Df} in the flow was determined by a calculation involving the initial moisture content and the amount of evaporated liquid, by using the available formulas or graphs [7–9]. The curves in Fig. 2 show the variation of P_{DF} and P_{Df} along the tube for several regimes.

Determination of the local values of the mass transfer coefficient necessitated the use of the mean values of Q_D (or $G_D = Q_D/r$), P_{DF}, and P_{Df} for the particular section, and it is obvious that, the shorter the sections, the more accurate the result will be. Several graphs of local mass transfer coefficients calculated in this way are shown in Fig. 2.

It should be borne in mind that averaging of β_p from formula (2) and as the mean integral of the local values, according to the relationship

$$\beta_p = \int_0^L \beta_{px}\, dx/L, \tag{3}$$

leads to different quantitative results, as is also the case with the heat transfer coefficient [10].

The aim of the subsequent calculations was to represent the experimental mass transfer data in the form of generalized quantitative relationships. It should be noted that owing to the higher fluxes of diffusing substance (water vapor) the problem becomes more complex than for the case of the similar low-rate process, when it is possible to use the thermal diffusion analogy. It is known [6–9, 11–16] that at high fluxes of diffusing substance there are several features which destroy the analogy between mass transfer and pure heat transfer, and this effect is greater, the more rapid the mass transfer. This can be taken into account by various methods based on an analysis of the effect with the adoption of certain physical hypotheses and simplifications. In particular, a widely used method is that of introducing additional criteria, the best known of which is a thermodynamic criterion of the form

$$\mathrm{Gu} = (T_{mix} - T_{mass})/T_{mix}, \tag{4}$$

called the Gukhman number [7, 8, 11–14], a system of dimensionless parameters [9, 15, 16]

$$\Pi_D = \frac{\Delta P_D}{P_{mix}}, \quad \varepsilon_g = \frac{P_g}{P_{mix}} \text{ and } \frac{R_D}{R_g}, \tag{5}$$

and parametric criteria [17–28]

$$P_{mix}/P_{gm} \quad \text{or} \quad P_{gF}/P_{gm}. \tag{6}$$

It is very remarkable that all the above criteria are related to one another or replaceable by one another, as is revealed by plots of them against the parameter P_{DF} (or t_F), which is one of the mean physical characteristics of the process. The plots shown in Fig. 3 are for the case of evaporation of water in air at normal pressure ($P_{mix} = 1.013 \cdot 10^5$ N/m²) and with varying vapor content. The curves of $\mathrm{Gu} = f(P_{DF})$ were plotted by using the following relationship:

$$P_{DF} = \frac{\alpha}{\beta_p}\,\frac{T_{mix} - T_{mass}}{r} + P_{Df}, \tag{7}$$

obtained from the condition for heat balance on the gas-liquid boundary in the case of adiabatic evaporation of the liquid. The ratio α/β_p is determined by joint solution of the criterial equations for heat and mass transfer, as shown in [21]. The relationship (7) can be reduced by simple transformations to the following form, which is more convenient for practical calculations:

$$P_{DF} = P_{mix} - \frac{P_{gf}}{\lambda_{gf}\,\Delta t/P_{mix} k_p r + 1}. \tag{8}$$

The calculation was performed by successive approximations by assigning different values to T_{mix} and subsequent determination of T_{mass} so that relationship (8) is satisfied.

In addition, it follows from the cited data that the numerical values of the criteria are stratified in relation to P_{Df} (or P_{gf}), which is clearly illustrated by the point made in [15], viz., that it is not sufficient to introduce only one of them into the criterial equation of mass transfer. In the general case the simplex P_{gf}/P_{mix} must be introduced along with one of them.

A characteristic feature of the criterion P_{mix}/P_{gm} is that it is more sensitive to the change in temperature of the evaporating liquid than the others. The Gu number, which relates to the special case of adiabatic evaporation of the liquid, differs from the other criteria in that it requires the value of an additional parameter—the flow temperature T_{mix}.

This provides some basis for the conclusion that the set of criteria P_{mix}/P_{gm} ($\Delta P_D/P_{mix}$ or P_{gF}/P_{gm}) and P_{gf}/P_{mix}, which take into account all the main parameters of the mass transfer process, must be of a most general character and may be used, in particular, for treatment and generalization of the results of the common natural process of adiabatic evaporation of a liquid (together, of course, with the Gukhman number, which is used at present for this case).

On the basis of the above considerations the set of parameters P_{mix}/P_{gm} and P_{gf}/P_{mix} was chosen as additional criteria for treatment of the results of the present experiments.

To exclude the effect of the liquid flow rate, the experiments were conducted in the narrowest possible range of flow rate—100–200 kg/m · hr—the minimum possible values in the case of intense evaporation.

In the region of small and moderate fluxes of diffusing substance, which is the case until the temperature of the film over a large part of its length exceeds 343–353° K, the parameters P_{mix}/P_{gm} and P_{gf}/P_{mix} differ little from unity. For treatment of data for vortex tubes with the same geometric characteristic

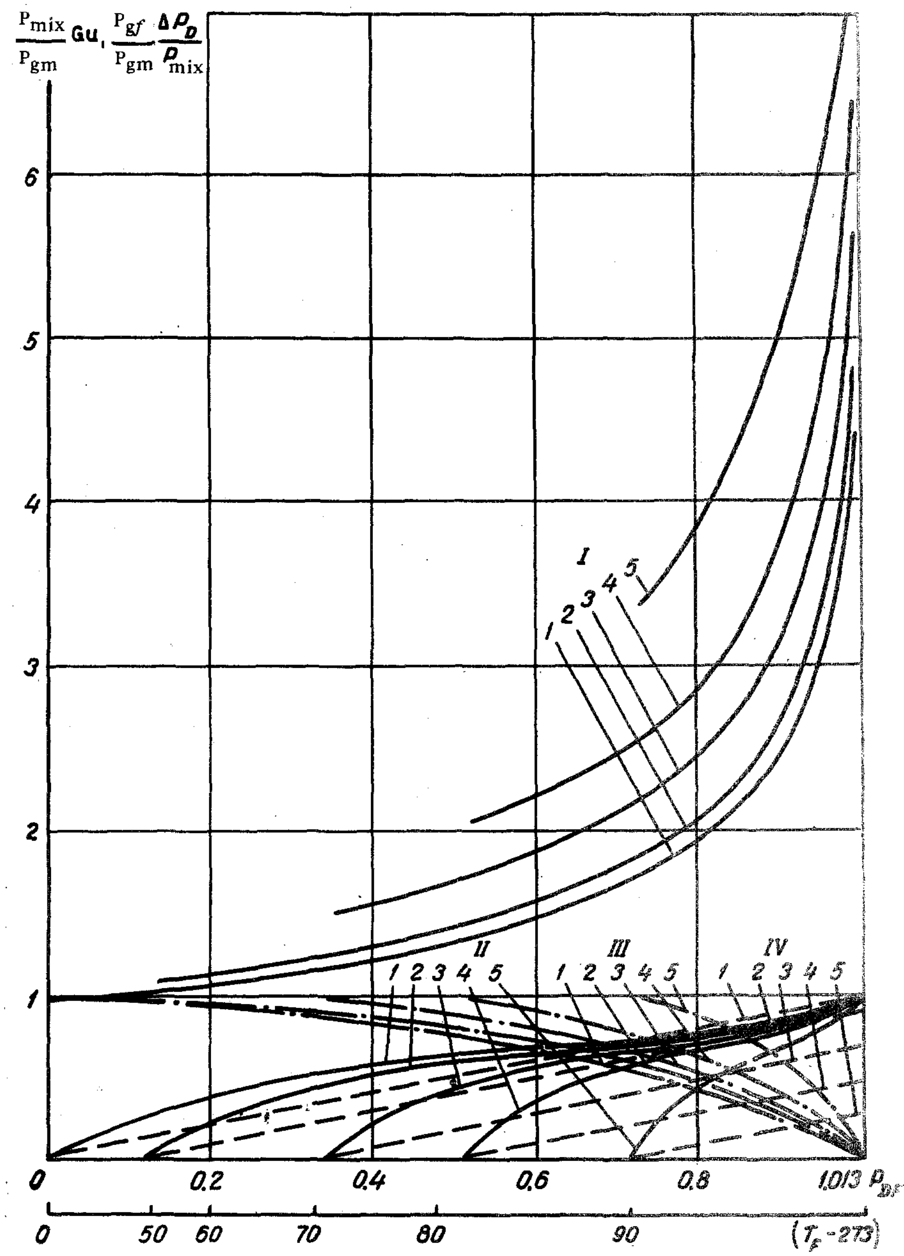

Fig. 3. Parametric criteria P_{mix}/P_{gm} (I), Gu (II), P_{gF}/P_{gm} (III), and $\Delta P_D/P_{mix}$ (IV) as functions of partial vapor pressure (or temperature) on film surface for $P_{mix} = 1.013 \cdot 10^5$ N/m² and different P_{Df}: 1) P_{Df} = = 0; 2) $1 \cdot 10^4$; 3) $3.3 \cdot 10^4$; 4) $5 \cdot 10^4$; 5) $7.1 \cdot 10^4$ N/m².

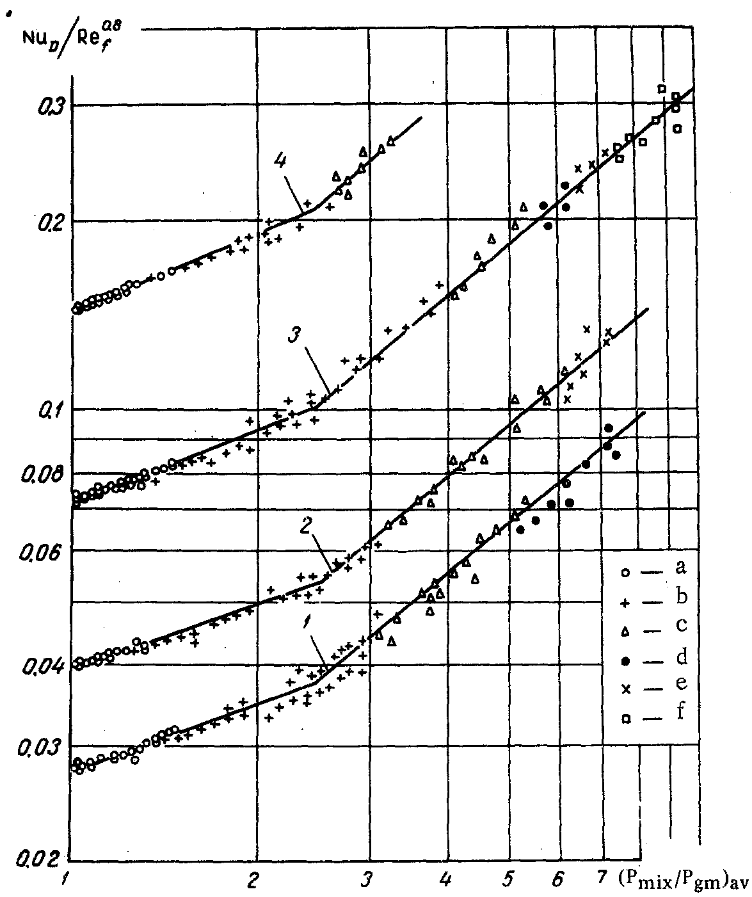

Fig. 4. Ratio $Nu/Re_f^{0.8}$ as a function of parameter $(P_{mix}/P_{gm})_{av}$ for different P_{gf}/P_{mix} (a – 0.9–10; b) 0.8–0.9; c) 0.7–0.8; d) 0.6–0.7; e) 0.5–0.6; and f) 0.4–0.5) and different vortex tubes: 1) L/D = 50 and $A_{h.t}$ = 0.4; 2) 50 and 1.2; 3) 20 and 2.5; 4) 20 and 20.6.

$A_{h.t}$ (or degree of twisting of the flow) and relative length L/D it is possible to use the usual criterial relationship of the form $Nu_D = f(Re_f)$. In this case the experimental points in logarithmic coordinates in the investigated range of variation of Re_f ($1 \cdot 10^3 - 1 \cdot 10^5$) lie, as was shown earlier [2], near straight lines parallel to that drawn from the equation

$$Nu_D = 0.019 Re_f^{0.8}, \qquad (9)$$

which is usually used in the case of the internal problem for calculation of the mass transfer from the surface of a water film to an axial flow of air [9].

In the calculations the physical parameters comprising the diffusion Nusselt number were determined at the average film temperature over the length of the tube. The parameters contained in the Reynolds number, which in this case was calculated from the diameter of the tube and the mean flow of vapor-gas mixture ($G_f = G_g + G_D/2$), were determined at the mean temperature of the latter with due allowance for the change in viscosity of the medium in relation to P_{Df}/P_{mix} from the approximate interpolation formula [29].

In parts of the tube where the film temperature rises above 343–353° K there is an appreciable increase in the numerical value of P_{mix}/P_{gm} and in the local heat transfer coefficients. This is illustrated for several regimes by the curves shown in Fig. 2. The effect of this criterion was assessed by treating the experimental data for $A_{h.t}$ = const and L/D = = const in the coordinates

$$\frac{Nu_D}{Re_f^{0.8}} = f\left[\left(\frac{P_{mix}}{P_{gm}}\right)_{av}\right], \qquad (10)$$

where $(P_{mix}/P_{gm})_{av}$ is the average integral value of P_{mix}/P_{gm} over the tube length. Some of the results are shown in Fig. 4.

The graphs indicate that the parameter P_{mix}/P_{gm} has a quite distinct and regular effect on the mass transfer. When $(P_{mix}/P_{gm})_{av}$ changes from 1 to 25 the measure of this effect, irrespective of $A_{h.t}$ and L/D, is a power of about 1/3, which for the last region covered by the experiment (2.5–10) increases to 0.8–0.85. Thus, with increase in the numerical value of P_{mix}/P_{gm} its effect on the rate of mass transfer becomes continuously greater.

The obtained result is readily understandable, since on the approach of the film temperature to the boiling point of the liquid at the given pressure the mass transfer coefficient and the parameter P_{mix}/P_{gm} increase without limit (this is also revealed by their local values at the hottest part of the tube) and tend to infinity when these temperatures become equal. This corresponds physically to the onset of a new phenomenon—surface boiling of the liquid film [30]. Thus, it can be concluded that the straight lines shown in Fig. 4 are an approximation for only the experimentally examined, predominantly initial range of the continuously progressing relationship between Nu_D and P_{mix}/P_{gm}.

Despite the inclusion of the parameter P_{gf}/P_{mix} among the characteristic criteria, the conducted experiments do not reveal the nature of its effect on mass transfer. The experiments were carried out in the region close to the saturated state of the vapor-gas mixture. This region would appear in Fig. 3 as a narrow band enveloping the lower boundaries of the curves $P_{mix}/P_{gm} = f(P_{DF})$. Hence, the parameter P_{gf}/P_{mix} varies simultaneously with the argument P_{mix}/P_{gm}, which is clearly illustrated in Fig. 4 by the position of the experimental points relating to different $(P_{gf}/P_{mix})_{av}$. The stratification of the points in relation to $(P_{gf}/P_{mix})_{av}$, observed in some cases where $(P_{mix}/P_{gm})_{av}$ = const, is commensurable with the scatter due to experimental errors and has a value of the order of ±10%. This prevents a separate and clear assessment of the effect of P_{gf}/P_{mix} on the mass transfer rate. Thus, in the investigated case, owing to the simultaneous and similar variation of the two parameters P_{gf}/P_{mix} and P_{mix}/P_{gm}, the experimental results can be generalized by introducing only one, the latter, into the critical equation.

It should be noted that with the adopted method of measuring the film temperature, which is accurate only to within ± 0.1° K at the hottest part of the tube, the error in determining local parameters in regimes close to the boiling point of the liquid is appreciably higher than the above-mentioned mean error for the whole tube owing to the very pronounced relationship $P_{DF} = f(t_F)$, and in some cases reaches 20–25%.

Finally, the criterial equation of mass transfer from the free surface of the water film to the vertical air flow for constant values of $A_{h.t}$ and L/D takes the following form:

$$Nu_D = c\, Re_f^{0.8}\left(\frac{P_{mix}}{P_{gm}}\right)_{av}^{k}, \qquad (11)$$

in which the numerical value of the coefficient mix is determined in relation to $A_{h.t}$ and L/D from the data given for the region of small transverse fluxes of diffusing substance in [2, 3]; the index of $(P_{mix}/P_{gm})_{av}$ has the values found in this paper, viz., k = 1/3 or 0.33 for $(P_{mix}/P_{gm})_{av}$ = 1–2.5 and k = 0.82 for $(P_{mix}/P_{gm})_{av}$ = 2.5–10. When treated in this way the experimental points for a given vortex tube ($A_{h.t}$ = = const, L/D = const) in the logarithmic coordinates $Nu_D/(P_{mix}/P_{gm})_{av}^k = f(Re_f)$ lie with a scatter of ±10–15%, on a straight line parallel to the straight line for axial annular two-phase flow, irrespective of the temperature conditions in the film.

NOTATION

D, L, $A_{h.t} = F_T/F_s$, F_T, F_w, and F_s are the diameter, length, geometric characteristic, area of cross section, area of internal wall of vortex tube, and total area of cross section of all tangential slits; Q_e, Q_{mix}, Q_D, Q_α, Q_r, and Q_L are the heat produced by electric heater, used up on heating, evaporation of liquid, convective heating of vapor-gas mixture, radiative heating of vapor-gas mixture, and heat loss to surroundings through insulation; G_D is the diffusive vapor flux; r is the heat of vaporization; P_{DF}, P_{Df}, and ΔP_D are the partial pressure of active (diffusing) component at film surface, in flow, and their difference; P_{gF}, P_{gf}, and ΔP_g are the same for inert component (air); $P_{gm} = \Delta P_g : \ln(P_{gf}/P_{gF})$ denote the mean logarithmic value of pressure of inert component in flow and at film surface; α, β_p, k_p, λ, and η are the heat transfer coefficient, mass transfer coefficient, diffusion coefficient, thermal conductivity, and dynamic viscosity; P_{mix} is the total pressure of mixture; R is the gas constant; $T_{mix} = t_f + 273$, $T_{mass} = t_F + 273$, and Δt are the absolute temperature of vapor-gas mixture, adiabatically evaporating liquid, and their difference; G_g and G_f are the flow rate of gas and vapor-gas mixture; G_l is the flow rate of liquid; $(P_{mix}/P_{gm})_{av}$ and $(P_{gf}/P_{mix})_{av}$ are the mean integral values over length of tube; $Nu_D = \beta_p D/k_p$ is the diffusion Nusselt number, $Re_f = 4G_f/\pi g D\eta_f$ is the Reynolds number of vapor-gas mixture. Subscripts D, g, F, and f denote parameters of active and inert components at the film surface and in the flow; 0 denotes the parameters at the tube entrance.

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