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HEAT TRANSFER ASSOCIATED WITH VAPOR CONDENSATION FROM VAPOR-GAS MIXTURES

I. A. Komarov

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Reports results of a theoretical analysis and experimental investigation of heat transfer accompanying vapor condensation from vapor-gas mixtures. Gives a dimensionless equation for estimating the surface necessary for vapor condensation in the presence of an inert gas.

It is known that the heat transfer accompanying vapor condensation from a vapor-gas mixture, just like that associated with condensation of pure vapor, always proceeds under conditions of heat transfer to the environment, the amount of heat given up by the vapor-gas mixture on cooling depending on its state. In particular, during cooling of a saturated vapor-gas mixture, both the heat of cooling of the mixture and the heat of condensation of the vapor are simultaneously transferred to the cooling surface. Usually, in practical calculations, determination of the over-all quantity of heat transferred to the cooling medium does not present any difficulty. But in determining the over-all surface required, both for cooling the mixture and condensation, one is always faced with the same problem: which kinetic equation should be used to calculate this surface – the equation of heat transfer or the equation of mass transfer.

In solving this problem we shall first, for the sake of simplicity, treat the simultaneous processes of cooling and vapor condensation as if they occurred separately, and write down for them two independent kinetic equations, expressing the cooling process by means of the equation of heat transfer

$$dQ_{\mathrm{a}} = K_{\mathrm{T}}(t - t_{\mathrm{c}})\,dF, \tag{1}$$

and the vapor condensation process by means of the equation of mass transfer

$$dG = \beta\,(W - W_{\mathrm{c}})\,dF. \tag{2}$$

Equation (2) can be written in the form

$$dQ_l = \beta\, r\,(W - W_{\mathrm{c}})\,dF. \tag{3}$$

Equations (1) and (2) show that, in the first case, the heat flux is related to the heat transfer potential via the kinetic heat transfer coefficient referred to the temperature difference, and in the second, via the kinetic mass transfer coefficient referred to the difference in moisture contents.

However, with this coupling of the heat fluxes and their transport potentials neither Eq. (1) nor Eq. (2) can be integrated, because the kinetic coefficients entering into these equations, referred respectively to the difference in temperatures and moisture contents, do not remain constant along the cooling surface during condensation of vapor from vapor-gas mixtures. The variability of the kinetic coefficient in Eq. (1) is due to the nonlinear change in the moisture content of the mixture with temperature, and in Eq. (3) to the nonlinear change in the specific heat of condensation with temperature.

So as to eliminate the influence of these factors, we shall refer the kinetic heat transfer coefficients not to the difference in temperatures and moisture contents, but to the corresponding heat potentials. Then Eqs. (1) and (2) can be written in the form

$$dQ_{\mathrm{a}} = K_{\mathrm{a}}\,[(c_p + c_{p_{\mathrm{v}}}W)\,t - (c_p + c_{p_{\mathrm{v}}}W_{\mathrm{c}})\,t_{\mathrm{c}}]\,dF \tag{4}$$

or

$$dQ_{\mathrm{a}} = K_{\mathrm{a}}\Delta\, i_{\mathrm{a}}dF, \tag{5}$$

$$dQ_l = K_l(rW - r_{\mathrm{c}}W_{\mathrm{c}})\,dF \tag{6}$$

or

$$dQ_l = K_l\Delta\, i_l dF. \tag{7}$$

Integrating Eqs. (5) and (7) with K_a = const, K_l = const (according to our experimental data K_a and K_l are constant) and taking their ratio, we obtain

$$K_{\mathrm{a}}/K_l = Q_{\mathrm{a}}\Delta\, i_l/Q_l\,\Delta\, i_l. \tag{8}$$

It is known that, in practical conditions, the heat transfer associated with vapor condensation from a vapor-gas mixture, as in normal convective heat transfer, takes place through molecular transport in a laminar sublayer and by turbulent transport in the core of the flow. Molecular transport in the relatively thin laminar sublayer formed directly at a phase discontinuity is known to proceed with only a slight transport potential gradient. We define t as the initial temperature of the saturated mixture in the laminar layer, which is cooled by direct phase contact with the cooling liquid to the temperature of the latter t_c. As a consequence of cooling and condensation, the vapor-gas mixture of the laminar sublayer loses heat. Therefore the following equalities hold:

$$\begin{gathered} Q_a = [(c_p + c_{p_v} W) t - (c_p + c_{p_v} W_c) t_c] G, \\ Q_l = (rW - r_c W_c) G. \end{gathered} \tag{9}$$

In this case, we get transfer of both apparent and latent heat from the saturated mixture of the laminar sublayer to the cooling surface owing to the presence of the corresponding enthalpy potentials Δi_a and Δi_l, which, thanks to the small gradients in the laminar layer, can be represented in the form

$$\begin{gathered} \Delta i_a = (c_p + c_{p_v} W) t - (c_p - c_{p_v} W_c) t_c, \\ \Delta i_l = rW - r_c W_c. \end{gathered} \tag{10}$$

From Eqs. (9)-(10), using Eq. (8), we have:

$$K_a/K_l = 1, \qquad \text{or} \qquad K_a = K_l = K'. \tag{11}$$

Following Eckert [2], we denote by V the volume of saturated vapor-gas mixture transported between two planes in unit time and through unit area, and by i_a, i'_a and i_l, i'_l, the apparent and latent heats in the planes considered. Then the apparent heat flux from the first plane to the second, determined by turbulent transport, is $q_a = v(i_a - i'_a)$. Expressing this heat flux by means of the kinetic coefficient of apparent heat transfer K_a, we have

$$K_a (i_a - i'_a) = V (i_a - i'_a). \tag{12}$$

The latent heat flux through unit area, also determined by turbulent transport, is $q_l = v(i_l - i'_l)$, and, expressing it in terms of the kinetic coefficient of latent heat transfer K_l, we have

$$K_l (i_l - i'_l) = V (i_l - i'_l). \tag{13}$$

From Eqs. (12) and (13) we also have $K_a/K_l = 1$, i.e., when the elementary kinetic coefficients of heat transfer accompanying vapor condensation from a saturated vapor-gas mixture are referred to the corresponding enthalpy gradients, the ratio of these coefficients for both turbulent and molecular transport is a constant equal to unity*. A numerical check on Eq. (11) using the experimental data of [4], obtained for a wide range of conditions of variation of vapor concentration in the saturated mixture and temperature of the cooling surface, completely confirmed the applicability of this rule to the process of vapor condensation from vapor-gas mixtures under the influence of a temperature gradient. At the same time, equality (11), obtained independently of the composition of the saturated vapor-gas mixture and constancy of the temperature of the cooling liquid, shows that mist formation in a flow of vapor-gas mixture cannot be caused by a change in the ratio of the kinetic coefficients of apparent and latent heat transfer of the process; this also follows from monograph [5] and from the experimental data of [5, 1, 4].

On the basis of Eq. (11), Eqs. (5) and (7), after integration, can be written in the form

$$Q_a = K' \Delta i_a F; \quad Q_l = K' \Delta i_l F. \tag{14}$$

In this case, the transported heat will all be comprised of heat transfer due to the apparent heat potential and heat transfer determined by the latent heat potential, i.e., $Q = Q_a + Q_l$. According to (14), $Q = K'(\Delta i_a + \Delta i_l)F$.

This equation includes two motive forces, but replacing them with the sum obtained by termwise addition of Eqs. (10), and denoting this sum by Δi, we have

$$Q = K' \Delta i F. \tag{15}$$

Equation (15) takes into account the heat transfer due both to cooling and condensation in conditions of unidirectional heat and mass transfer and, consequently, may be the basic equation of heat transfer accompanying vapor condensation from a vapor-gas mixture. In this case, the over-all heat transfer coefficient K', characterizing the rate of heat transfer with vapor condensation, in particular, for a packed scrubber at sufficiently high flow rates, in conformity

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*A similarity law relating the coefficients of apparent heat and mass transfer through the variable c_p was first demonstrated by Lewis [3] for adiabatic evaporation of water in air without a change in the temperature of the evaporating water during the process.

with the author's previous conclusions [4], and his experimental data, must depend on the variables a, μ, ρ, w, d, i and Δi, i.e., $K' = f\,(a, \mu, \rho, w, d, i, \Delta i)$ *.

Determination of the form of the generalized variables by dimensional analysis of the quantities involved enables one to reduce the equation to criterial form

$$\frac{K'd}{a} = C\left(\frac{a\rho}{\mu}\right)^{f}\left(\frac{wd}{a}\right)^{K}\left(\frac{\Delta i}{i}\right)^{h}, \tag{16}$$

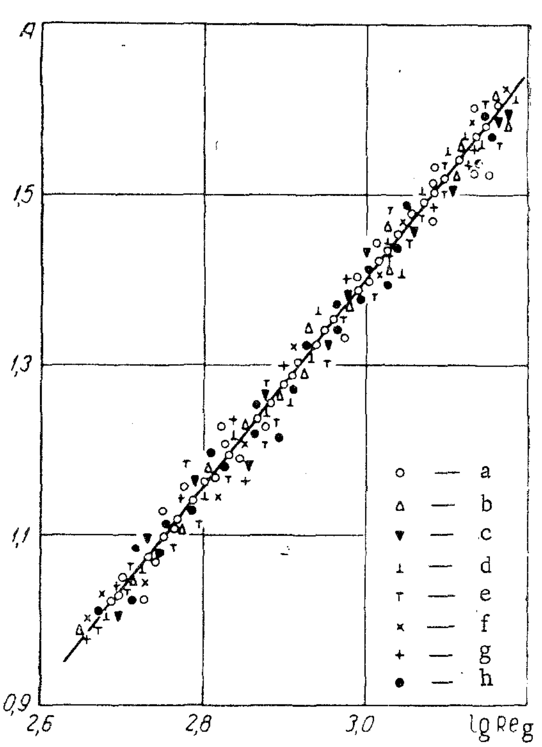
whence

$$\frac{K'd}{a} = C\left(\frac{\rho wd}{\mu}\right)^{m}\left(\frac{\Delta i}{i}\right)^{h}, \tag{17}$$

or in abbreviated notation

$$K_i' = C\mathrm{Re}_g^m S_{\Delta i}^h. \qquad (18)^{**}$$

To determine numerical values of the coefficient C and the exponents m and h, we carried out an experimental investigation of heat transfer, complicated by vapor condensation from a vapor-gas mixture, at different gradients of apparent and latent heat and velocities of the vapor-gas mixture. Experiments were carried out in a packed scrubber D_{in} = 257 mm on air saturated with water vapor and cooled with water. In accordance with the temperature conditions adopted experiments were carried out in the range of mass vapor contents of the saturated air from 4.5 to 150.9% at the inlet and from 0.85 to 49% at the outlet. In these experiments the upper part of the scrubber was at atmospheric pressure. The gas and cooling water loads correspond successively to intermediate, turbulent, and emulsification conditions [7]. A detailed description of the experimental apparatus and the method of performing the experiments was given in [4]. The experimental data obtained were processed using Eq. (18).



Graph of log K_i − log $S_{\Delta i}^{0.15}$ ≡ A versus log Re_g at spraying rates ($m^3/m^2 \cdot hr$) of: a) 16.2; b) 21.5; c) 28.8; d) 32.2 (height of packing − 750 mm); e) 16.2; f) 21.5; g) 28.8; h) 32.2 (height of packing − 970 mm).

In processing the experimental data, we referred the physical constants of the vapor-gas mixture to a temperature corresponding to the logarithmic mean value of the enthalpy of the vapor-gas flow. The figure shows that the experimental points for all the series are consistent and fit a single straight line. Reduction of the experimental data allowed us to obtain the following design equation:

$$K_i' = 0{,}0075\,\mathrm{Re}_{\text{г}}^{1,15} S_{\Delta i}^{0,15}. \qquad (19)^{***}$$

NOTATION

K_T − kinetic heat transfer coefficient referred to temperature difference; K_a, K_l − kinetic heat transfer coefficients characterizing, respectively, the rate of transfer of apparent and latent heat; K' − over-all kinetic heat transfer coefficient referred to difference of enthalpies; Δi_a, Δi_l − apparent and latent heat potentials of core flow and equilibrium layer (dry gas); Δ_i − over-all enthalpy potential (dry gas); c_p, c_{pv}, c_p' − specific heats of dry gas, vapor, and mixture; W, W_c − moisture content of saturated mixture at mixture temperature t and temperature of cooling surface t_c; r, r_c − heat of condensation at temperatures of core flow and equilibrium layer; G − flow rate of dry gas; $K_i' = K'd_e/a$ − a new thermal similarity criterion; $d_e = 4\varphi/\sigma$ − equivalent diameter; φ − fraction of free volume; σ − surface area of packing in unit volume; a, μ, ρ − thermal diffusivity, viscosity, and density of vapor-gas mixture;

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*The diffusion coefficient D is not included in the relation, because, according to the experimental data, in condensation from a vapor-gas mixture due to cooling of the mixture molecular diffusion has no effect on the rate of the process.

**The nature and significance of the influence of the parametric criterion $S\Delta i$ on the intensity of complex heat transfer are discussed in [6].

***The exponents and coefficients of Eq. (19) differ from those in [14, 17]; in our work, for the convenience of practical calculation, the enthalpy of the vapor-gas mixture was referred to 1 m^3 of dry air, and not to 1 m^3 of mixture, as in [14, 17].

w — logarithmic mean velocity of vapor-gas mixture referred to total cross section of absorption tower; $S_{\Delta i}$ — parametric enthalpy criterion; i—logarithmic mean volume enthalpy of vapor-gas mixture (dry gas); $\Delta i = (\Delta i_i - \Delta i_f)/ /2.3 \lg(\Delta i_i/\Delta i_f)$ — logarithmic mean difference in enthalpy between core flow and equilibrium layer (dry gas); Δi_i, Δi_f — initial and final difference in enthalpy between core flow of vapor-gas mixture and equilibrium layer at cooling surface (dry gas).

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Lensovet Technological Institute,
Leningrad