CONDENSATION OF A BINARY MIXTURE OF IMMISCIBLE FLUID VAPORS

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The nature of the variation in temperature differential is established around the perimeter and along the length of tubes. Analytic formulas are obtained for the local and mean heat transfer coefficients during the condensation of a vapor mixture such as benzene–water in horizontal and vertical tubes. An estimate is made of the effect of nonisothermality.

In the theoretical analysis of the condensation of a binary vapor mixture such as benzene–water [1-5], it assumed that the wall temperature and the temperature differential through the condensate layer are constant both around the perimeter and along the length of a tube. It is well known [6] that the assumption Δt = const does not lead to significant error in the determination of the mean value of the heat transfer coefficient for film condensation of a pure vapor.

Visual observations made it possible to establish [1-3, 5] that the organic component of the binary ordinarily forms a film on the condensation surface and the water forms drops on this film. (A photograph of the condensation of a mixture of benzene–water vapors on a horizontal tube with D = 0.024 m is shown in Fig. 1.) This results in a large nonuniformity of wall temperature in comparison with film condensation of pure vapors.

Experimental studies of the variation of wall temperatures around the perimeter of a horizontal tube during the condensation of vapors of water, benzene, and various vapor mixtures such as benzene–water, toluol–water, trichlorethylene–water, heptane–water [7], benzene–water [5], and turpentine–water [8], and along the length of a vertical tube for vapor mixtures of benzene–water and toluol–water [1] showed the periodic nature of this variation.

From an analysis of experimental data [5, 7, 8], we have established that for a horizontal tube the relationship $t_W = f(\varphi)$ is identical for both the condensation of pure vapors and the condensation of mixtures (Fig. 2) and can be described by the simple empirical formula

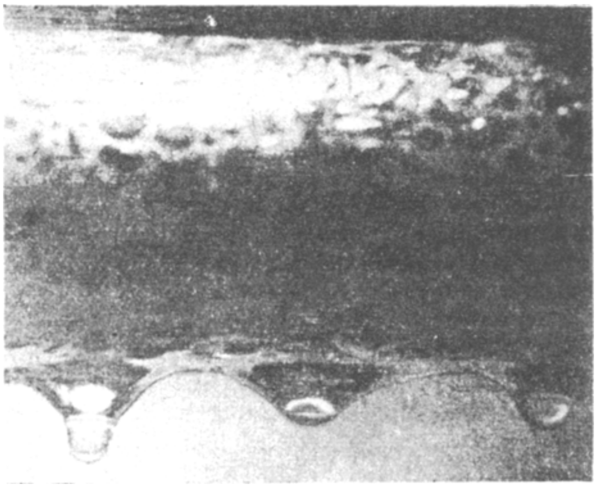

Fig. 1. Condensation of benzene–water vapor mixture in a horizontal tube with D = 0.024 m. Experiment No. 220 [5], b = 0.471; t''_s = 67.5°C; $\bar{t}_W$ = 61.7°C; $\bar{\Delta} t$ = 5.8°C; α_{exp} = 5796 W/m^2·deg.

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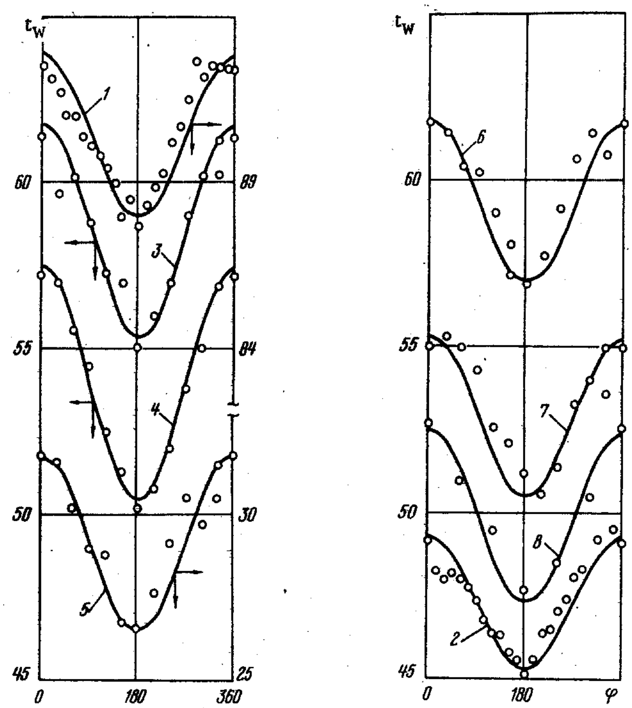

Fig. 2. Variation of t_w around the perimeter of a horizontal tube. Points are experimental data: 1) water [7], $\overline{\Delta t}$ = 10.5°C, ω = 0.26; 2) benzene [7], $\overline{\Delta t}$ = 32.7°C, ω = 0.08; 3) toluol—water [7], $\overline{\Delta t}$ = 24.5°C, ω = 0.12; 4) trichlorethylene—water [7], $\overline{\Delta t}$ = 19°C, ω = 0.17; 5) heptane—water [7], $\overline{\Delta t}$ = 50.4°C, ω = 0.05; 6) turpentine—water [8]; 7) benzene—water [7], $\overline{\Delta t}$ = 15.7°C, ω = 0.15; 8) benzene—water [5], $\overline{\Delta t}$ = 5.8°C, ω = 0.37; curves are calculated from Eq. (1).

$$t_w = \bar{t}_w + C_1 \cos \varphi. \tag{1}$$

The experimental data [1] which establish the nature of the variation of t_w along the length of a vertical tube are completely satisfactorily approximated by the polynomial (Fig. 3)

$$t_w = \bar{t}_w + C_2 + C_3 \left(\frac{x}{H}\right) + C_4 \left(\frac{x}{H}\right)^2. \tag{2}$$

The selection of Eqs. (1) or (2) and the determination of the constants C_i appearing in them are made on the basis of well-known rules for analysis of experimental data [9].

For a horizontal tube, the value of $\bar{t}_w$ calculated over the entire perimeter is very close to the values of t_w at $\varphi = \pi/2$ and $3\pi/2$. The value of C_1 can be defined as $C_1 = 0.5\,(t_{w\max} - t_{w\min})$ or $C_1 = t_{w\max} - \bar{t}_{w\min}$. The local and mean values of the temperature drop between vapor and wall are related by

$$\Delta t = \overline{\Delta t}\left(1 - \frac{C_1}{\overline{\Delta t}} \cos \varphi\right) = \overline{\Delta t}\,(1 - \omega \cos \varphi). \tag{3}$$

For a vertical tube, $C_2 = t_{w\max} - \bar{t}_w$. In accordance with Eq. (2),

$$\Delta t = \overline{\Delta t}\left[1 - \omega - \frac{C_3}{\overline{\Delta t}}\left(\frac{x}{H}\right) - \frac{C_4}{\overline{\Delta t}}\left(\frac{x}{H}\right)^2\right] = \overline{\Delta t}\,[\chi(x)]\,. \tag{4}$$

The analytic solution of the problem of determining the local and mean coefficients of heat transfer for condensation of a binary mixture of vapors of immiscible fluids on an isothermal surface is obtained [5], as is well known, under a series of assumptions and simplifying assertions.

Using such a two-film model [4, 5] and solution technique for the case of a nonisothermal surface, we establish the effect of the variation in t_w, and consequently of the variation in Δt, on the value of the local

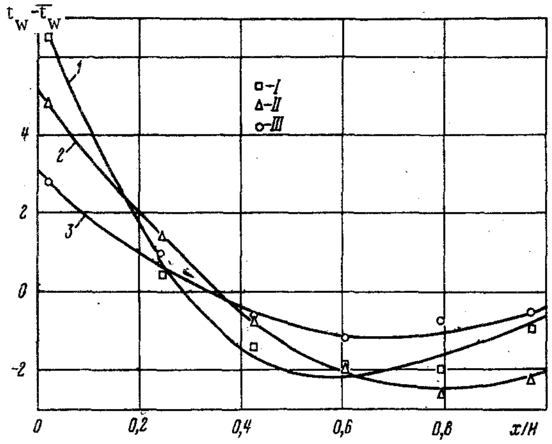

Fig. 3

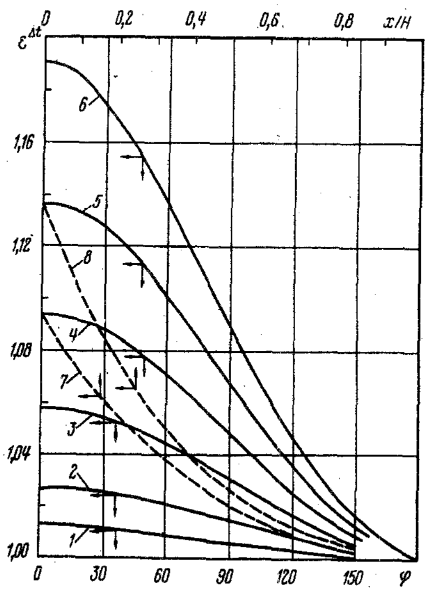

Fig. 4

Fig. 3. Variation of $t_w - \bar{t}_w$ along the length of a vertical tube. Experimental data [11]: I) benzene—water ($b = 0.10$; $\overline{\Delta t} = 18.6°C$, $\omega = 0.40$); II) toluol—water ($b = 0.28$, $\overline{\Delta t} = 18.9°C$, $\omega = 0.27$); III) benzene—water ($b = 0.524$, $\overline{\Delta t} = 7.3°C$, $\omega = 0.41$). Curves are calculated from Eq. (2): 1) $C_2 = 7.2$; $C_3 = -2.9$; $C_4 = 21.0$; 2) $C_2 = 5.2$, $C_3 = -8.4$, $C_4 = 11.0$; 3) $C_2 = 3.0$, $C_3 = -11$, $C_4 = 8.4$.

Fig. 4. Values of local $\varepsilon_H^{\Delta t} = f(\varphi)$ and $\varepsilon_V^{\Delta t} = f(x/H)$. Solid curves are for a horizontal tube in accordance with Eq. (7) where 1) $\omega = 0.005$; 2) 0.1; 3) 0.2; 4) 0.3; 5) 0.4; 6) 0.5; dashed curves are for a vertical tube in accordance with Eq. (13) and experimental data [1], 7) $\omega = 0.3$; 8) 0.4.

and mean heat-transfer coefficients. We assume the velocity distribution in the condensate layer remains as before [5].

From the equality of the heat deposited during condensation of the vapor mixture and the heat removed by thermal conductivity through the condensate layer to the wall, we obtain a differential equation which describes the variation of condensate layer thickness over the perimeter of a nonisothermal horizontal tube,

$$\frac{d\delta}{d\varphi} = \frac{BR_0(1-\omega\cos\varphi) - \delta^4\cos\varphi}{3\delta^3\sin\varphi}, \tag{5}$$

where

$$B = \frac{3\lambda_2\mu_2\overline{\Delta t}\left(1+\dfrac{\rho_2}{\rho_1 A}\right)^4}{g^2\rho_2^2 r_2\left[1+b\left(\dfrac{r_1}{r_2}-1\right)\right]\left(1+\dfrac{\lambda_2\rho_2}{\lambda_1\rho_1 A}\right)\left(1+\dfrac{3m}{A}\right)} = \frac{3\lambda_2\mu_2\overline{\Delta t}M^4}{g^2\rho_2^2 r_2\beta_0 N\left(1+\dfrac{3m}{A}\right)}.$$

Bringing Eq. (5) into the Bernouilli form and solving it by the Fourier method, we obtain an expression for δ and a formula for the local heat-transfer coefficient in condensation of a binary mixture of vapors of immiscible fluids on a horizontal nonisothermal tube in the following form:

$$\alpha_H^{\Delta t} = \frac{\lambda_1}{N}\sin^{1/3}\varphi\left[\frac{4B}{3}\int_0^{\varphi}\sin^{1/3}\varphi(1-\omega\cos\varphi)\,d\varphi\right]^{-\frac{1}{4}}. \tag{6}$$

Analysis of the resultant solution and that in [5] makes it possible to establish an expression for the ratio of local heat-transfer coefficients in condensation on horizontal isothermal and nonisothermal tubes:

$$\varepsilon_{H}^{\Delta t}=\frac{\alpha^{\Delta t}{}_{m_H}}{\alpha\ m_H}=\left[\frac{\int_0^{\varphi}\sin^{1/3}\varphi d\varphi}{\int_0^{\varphi}\sin^{1/3}\varphi(1-\omega\cos\varphi)\,d\varphi}\right]^{\frac{1}{4}}=\left[1-\frac{3\omega\sin^{4/3}\varphi}{4\int_0^{\varphi}\sin^{1/3}\varphi d\varphi}\right]^{\frac{1}{4}}. \tag{7}$$

It appears from Eq. (7) that the composition of the vapor mixture and the thermophysical properties of the components have no direct effect on the quantity $\varepsilon_H^{\Delta t}$. However, one can suppose that this effect shows up indirectly in C_1 and ω.

The results of calculations based on this equation using the tables in [10] are shown in Fig. 4 for cases where the nonisothermality parameter is $0.05 \le \omega \le 0.5$. The maximum values of the ratio of the local heat-transfer coefficients for nonisothermal and isothermal cases fall in the range $\varepsilon_H^{\Delta t} = 0.114$–$1.192$. According to published data [5, 7], the practically probable range of the nonisothermality parameter is $\omega = 0.05$–0.4. This leads to an error of as much as 13.7% in the determination of the local heat-transfer coefficient when nonisothermality is not considered. The value of $\varepsilon_H^{\Delta t}$ are greatest for the upper portion of the tube $(0 \le \varphi \le 120)$, which plays a fundamental role in heat transfer. It is therefore necessary to take into account the effect of nonisothermality in the calculation of local α_{W_H} if $\omega \ge 0.2$. We find from Eq. (6) that the mean heat-transfer coefficient over the perimeter of a tube for a mixture when $\Delta t = \text{var}$ is

$$\bar{\alpha}^{\Delta t}_{m_H}=\frac{1}{\pi}\int_0^{\pi}\alpha^{\Delta t}_{m_H}\,d\varphi=\frac{\lambda_2}{\pi N}\int_0^{\pi}\frac{\sin^{1/3}\varphi d\varphi}{\left[\frac{4B}{3}\int_0^{\varphi}\sin^{1/3}\varphi(1-\omega\cos\varphi)\,d\varphi\right]^{\frac{1}{4}}}. \tag{8}$$

In such a case, the equation for the determination of the ratio of the mean heat-transfer coefficients in nonisothermal and isothermal horizontal tubes takes the form

$$\bar{\varepsilon}^{\Delta t}_{H}=0.3674\int_0^{\pi}\frac{\sin^{1/3}\varphi d\varphi}{\left[\int_0^{\varphi}\sin^{1/3}\varphi d\varphi-\frac{3\omega\sin^{4/3}\varphi}{4}\right]^{\frac{1}{4}}}. \tag{9}$$

Calculations based on this equation show that $1.012 \le \bar{\varepsilon}_H^{\Delta t} \le 1.115$ when $0.05 \le \omega \le 0.50$. Furthermore, $\bar{\varepsilon}_H^{\Delta t} > 1.06$ if $\omega > 0.3$.

Substituting Eq. (4) in the equation of heat balance for a vertical tube, we obtain after transformations the following differential equation describing the variation of condensate layer thickness along the length of a tube:

$$\delta^3\frac{d\delta}{d\varphi}=\frac{B}{3}\,[f(x)]. \tag{10}$$

After solving Eq. (10) we have an expression for δ and finally equations for the local mean heat-transfer coefficients of the mixture including consideration of the nonisothermality of the condensation surface:

$$\alpha^{\Delta t}_{m_V}=\frac{\lambda_2 M}{N}\left(\frac{3}{4B}\right)^{\frac{1}{4}}\left\{\int_0^x[f(x)]\,dx\right\}^{-\frac{1}{4}}, \tag{11}$$

$$\bar{\alpha}^{\Delta t}_{m_V}=\frac{1}{H}\int_0^H\alpha^{\Delta t}_{m_V}\,dx=\frac{\lambda_2 M}{NH}\left(\frac{3}{4B}\right)^{\frac{1}{4}}\int_0^H\frac{dx}{\left\{\int_0^x[f(x)]\,dx\right\}^{\frac{1}{4}}}. \tag{12}$$

Comparison of Eqs. (11) and (12) with the corresponding expressions which are obtained by solution of Eq. (10) for $\Delta t = \text{const}$ yields the following expressions for the local and mean corrections for the effect of nonisothermality in a vertical tube:

$$\varepsilon^{\Delta t}_{V}=\left\{\frac{1}{x}\int_0^x[f(x)]\,dx\right\}^{-\frac{1}{4}}, \tag{13}$$

$$\bar{\varepsilon}_{V}^{\Delta t} = \frac{3}{4H^{3/4}} \int_0^H \left\{ \int_0^x [f(x)] \, dx \right\}^{-\frac{1}{4}} dx. \quad (14)$$

According to data in [1], values of the nonisothermality parameter for vertical tubes are $0.16 \leq \omega \leq 0.46$. In this case, $1.05 \leq \varepsilon_V^{\Delta t} \leq 1.18$ and $1.02 \leq \bar{\varepsilon}_V^{\Delta t} \leq 1.06$.

The dashed curves in Fig. 4 show the variation of the local values of $\varepsilon_V^{\Delta t}$ as a function of the variation of the relative distance x/H from the upper and of a tube for the two cases $\omega = 0.3$ and $\omega = 0.4$. Values of the constants appearing in Eq. (4) were determined from specific experimental data [1]. It is clear from the figure that the variation of $\varepsilon^{\Delta t}$ for horizontal tubes is different from that for vertical tubes. But one should note that the maximum values of local $\varepsilon_H^{\Delta t}$ and $\varepsilon_V^{\Delta t}$ are equal for identical values of the nonisothermality parameter while $\bar{\varepsilon}_H^{\Delta t}$ and $\bar{\varepsilon}_V^{\Delta t}$ are different.

This theoretical analysis allows one to establish that in first approximation the effect of nonisothermality on the value of the local heat-transfer coefficient for the condensation of a mixture of vapors of immiscible fluids is significant for a nonisothermality parameter $\omega > 0.3$ in the region $0 < \varphi < 2\pi/3$ for horizontal tubes and in the region $0 < x/H < 0.5$ for vertical tubes. This is explained by the fact the thickness of the condensate layer is much greater in the lower portion of a tube than in the upper portion.

The effect of isothermality on the magnitude of the mean heat-transfer coefficient of a vapor mixture for laminar flow of the condensate can be considered insignificant as in the case of film condensation of pure vapors [6].

NOTATION

φ	is the angle calculated from upper point of horizontal tube;
x	is the current coordinate;
H	is the height of the tube;
R_0	is the external radius of tube;
t_w, $\bar{t}_w$	are the local and mean values of wall temperature;
Δt, $\bar{\Delta} t$	are the local and mean values of temperature drop between vapor and wall;
$\omega = t_{w_{max}} - \bar{t}_w / \bar{\Delta} t$	is the nonisothermality parameter;
$C_i (i = 1, 2, \ldots, 4)$	is the constant determined from particular experimental conditions;
$\delta = \delta_1 + \delta_2$	is the thickness of condensate layer;
g	is the gravity constant;
b	is the weight fraction of water in condensate;
ρ_1, ρ_2	are the water and organic component density;
λ_1, λ_2	are the thermal conductivity of water and organic component;
r_1, r_2	are the latent heat of evaporation of water and organic component;
μ_2	is the dynamic viscosity of organic fluid;
α_m, $\bar{\alpha}_m$	are the local and mean heat transfer coefficients of mixture;
$\varepsilon^{\Delta t}$, $\bar{\varepsilon}^{\Delta t}$	are the local and mean correction for nonisothermality,
$A = \rho_2\delta_2/\rho_1\delta_1$	is the function for dependence between thickness of organic film δ_2 and equivalent thickness of water film δ_1.

Subscripts

w	denotes the wall;
max	denotes the maximal;
min	denotes the minimal;
m	denotes the mixture;
H	denotes the horizontal;
V	denotes the vertical.

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