HEAT TRANSFER IN CONDENSATION ON THE EXTERNAL SURFACE OF HORIZONTAL TUBES

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A relation taking account of the intensification of heat transfer on account of waves at the lower and lateral surfaces of tubes is obtained.

Comparison of experimental data on heat transfer obtained in the condensation of motionless water and khladon vapor with the same Reynolds numbers (KPr > 5) reveals a discrepancy between these data themselves and also with the results obtained by calculational methods [1]. The most widespread method of calculating the mean heat transfer takes account of undulation at the lateral surface only for tubes satisfying the condition $We^{-1/2} \geq 20$ [2]. The correction factor introduced in this case for the Nusselt formula is some function of the Reynolds number

$$\overline{\mathrm{Nu}} = 0{,}95\,\mathrm{Re}^{0,04}\overline{\mathrm{Nu}}_N. \tag{1}$$

This approach to calculating condensation gives two dependences for the heat transfer in tubes of large ($We^{-1/2} \geq 20$) and small diameter, with no systematic transition between them. Experimental investigation of the condensation of Khladons [3] shows increase in heat transfer on account of wave motion of the condensate even when $We^{-1/2} < 10$. These findings and the available theoretical results [4] lead to the conclusion that the method employed in [2] needs refinement.

Retaining the general structure of the method of calculating the mean heat transfer, when the change in thermophysical properties of the condensate, the convective acceleration of its particles, and the wave of the phase interface are taken into account by introducing the corresponding correction factors to the Nusselt formula, the following expression may be written

$$\overline{\mathrm{Nu}} = \varepsilon_t \varepsilon_i \varepsilon_v \overline{\mathrm{Nu}}_N. \tag{2}$$

When KPr > 5, ε_t and ε_i are close to unity, and the presence of spatial instability of the condensate film leads to growth in heat transfer on account of increase in the phase-interaction surface and convective motion at the lower generatrix and lateral surface of the horizontal tube. The latter factor is taken into account as follows in calculating the heat transfer

$$\varepsilon_v = 1 + \varepsilon_{v,b} + \varepsilon_{v,s}, \tag{3}$$

where $\varepsilon_{v,b}$, $\varepsilon_{v,s}$ are determined by the characteristics of the waves and the conditions of their appearance at the lower generatrix and lateral surface, respectively.

As shown in [5], at the coolant flow rates realized in the operation of heat exchangers in nominal conditions, practically motionless waves appear at the lower generatrix of the horiziontal tube; the wave characteristics, found by a method analogous to that in [5], satisfy the following relation when $We^{-1/2} \gg 2\delta$

$$\frac{\omega^2}{k^2\delta} = k^2 + 4\,\mathrm{We} - 2\,\frac{\mathrm{Ka}^{-1/2}}{(\mathrm{KPr})^2}\left(\frac{\rho_1}{\rho_2} - 1\right)\delta^{-3} + 1. \tag{4}$$

Dispersion Eq. (4) takes account of the curvature of the condensate surface and the reactive force of phase transition. Analysis of Eq. (4) at the extremum allows the dominant (with maximum growth rate) wavelength to be isolated

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$$l_d = \frac{2\pi}{k_d} = 2\pi\left\{2\left[1 + 4\,\mathrm{We} - 2\frac{\mathrm{Ka}^{-1/2}}{(\mathrm{KPr})^2}\left(\frac{\rho_1}{\rho_2} - 1\right)\delta^{-3}\right]^{-1}\right\}^{1/2}. \tag{5}$$

The presence of the dominant perturbation leads to discrete runoff of condensate from the lower generatrix of the tube, and the most probable distance between the centers of jet or drop formation is determined by the dominant wavelength. The result obtained in Eq. (5) with We = 0 and K = ∞ coincides with the expression characterizing a Taylor wave for thin liquid films [6].

Taking account of the small reactive force of phase transition in the condensation processes realized in technical devices, it is found that

$$l_d \doteq 2\pi\sqrt{\frac{2}{1 + 4\mathrm{We}}}. \tag{6}$$

For comprehensive testing of the resulting expression, experiments are undertaken allowing the influence of the thermophysical properties and tube diameter of the condenser on the dominant wavelength to be determined. In the first case, the variation in temperature of the liquid fed inside the porous cylinder simulates the runoff of condensate from the lower generatrix of the tube. In the second, the condensation of saturated vapor is investigated at horizontal tubes of the following diameter, m: $4\cdot10^{-3}$, $6.4\cdot10^{-3}$, $8.4\cdot10^{-3}$, $1.22\cdot10^{-2}$. The dominant wavelength is determined as a result of statistical analysis of the experimental data for the distance between the centers of the departing drops or jets on photographic prints, in accordance withthe scale. The experimental results obtained (Fig. 1) give good agreement with calculations by Eq. (6): the maximum deviation of the statistical mean of l_d from Eq. (6) is no more than 10-12%.

The appearance of instability in condensate flow over the lateral surface of a horizontal tube was considered in [4]. It may be shown that, for $\mathrm{We}^{-1/2} > 4$, phase-interface waves develop at Reynolds numbers greater than

$$\mathrm{Re}_v = \left(\frac{43}{\pi}\,\mathrm{Ka}^{1/30}\right)^{1,06}, \tag{7}$$

beginning at the angle

$$\theta_v = 43\,(\mathrm{Re}\,\mathrm{Ka}^{-1/30})^{-0,94}. \tag{8}$$

Using Eqs. (7) and (8), sections with purely laminar and undulatory flow of the condensate may be distinguished in calculating the heat transfer.

In the case of purely laminar condensate flow over the lateral surface ($\mathrm{Re} < \mathrm{Re}_v$, $\varepsilon_{v,s} = 0$), intensification of the heat transfer occurs only on account of wave formation at the lower generatrix. At small Re, increase in heat transfer is associated principally with increase in surface area of the phase interface. In the case of drop runoff, the relative proportion of increase in phase interface is

$$f = \frac{\pi DL + L\bar{F}/l_d l_\sigma}{\pi DL} = 1 + \frac{F}{\pi D l_d l_\sigma}, \tag{9}$$

where $\bar{F} = 5.4\pi l_\sigma^2$ is the mean surface of a spherical drop after it grows to a diameter corresponding to breakaway ($3l_\sigma$ [6]).

Using Eqs. (9) and (6), the first approximation for the correction factor is found from Eq. (3)

$$\varepsilon'_{v,b} = \frac{1,35}{\pi}\sqrt{2\mathrm{We}\,(1 + 4\mathrm{We})}. \tag{10}$$

In Fig. 2, the results of calculating the heat transfer according to Eqs. (2), (3), and (10) are compared with experimental data satisfying the condition $\mathrm{Re} = 10 < \mathrm{Re}_v$ [3]. Deviation of the experimental values when $\mathrm{We}^{-1/2} < 2$ is associated with reduction in the dominant wavelength in Eq.(6) to a value close to the drop diameter, their partial coalescence, decrease in surface of the phase interphase and consequently increase in the thermal resistance. This constraint on the use of Eq. (10) does not extend to power equipment, since the tubes used there are not so thin.

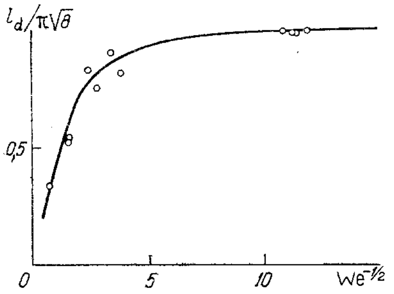

Fig. 1

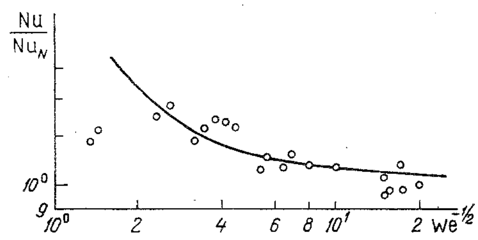

Fig. 2

Fig.1. Dependence of the dominant wavelength on the Weber criterion: the points correspond to experiment and the curve to Eq. (6).

Fig.2. Influence of growth in the surface of the phase interface on the heat transfer when Re= 10: the curve corresponds to Eqs. (2), (3), and (10) when $\varepsilon_{v,s} = 0$ and the points to experiment [3].

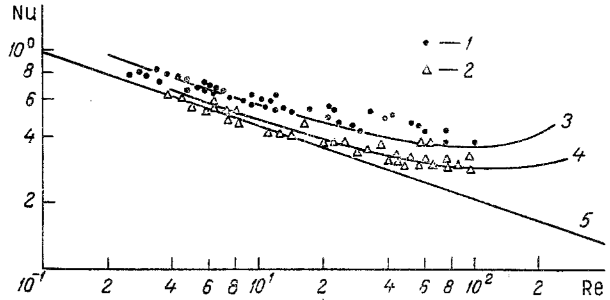

Fig. 3. Comparison of calculations by the present method with experimental data [7, 8]: 1) Freon-12, D = 0.006 M (Ka $\approx 3\cdot10^9$, We$^{-1/2} \approx 7$); 2) Freon-21, D = 0.016 M (Ka $\approx 6\cdot10^{10}$, We$^{-1/2} \approx 16$); 3) Calculation from Eqs. (2), (3), (12), and (13) when Ka = $3\cdot10^9$, We$^{1/2}$ = 7); 4) calculation from Eqs. (2), (3), (12), and (13) when Ka = $6\cdot10^{10}$, We$^{1/2}$ = 16; 5) calculation by Nusselt theory.

Growth in Reynolds number under the condition of laminar flow at the lateral surface leads to the appearance of convective mixing on account of increase in the amount of departing condensate and intensification of heat transfer. This effect, observed experimentally in [3], allows Eq. (10) to be corrected by introducing some power-law dependence on the Reynolds number

$$\varepsilon_{v,b} = \varepsilon'_{v,b} A\,\mathrm{Re}^m. \tag{11}$$

The constants found from the results of [3] are A = 1.0, m = 0.05.

Jet runoff of the condensate corresponds to an increase in phase interface that is somewhat different from Eq. (9). However, as shown by experiment, there is no pronounced change in heat-transfer law on transition from drop runoff to jet runoff. Hence, with any conditions of condensate runoff, intensification of heat transfer on account of waves at the lower generatrix of the tube is taken into account by the factor in Eq. (11), which is written in the following form after taking account of Eq. (10)

$$\varepsilon_{v,b} = \frac{1,35}{\pi}\sqrt{2\mathrm{We}\,(1+4\mathrm{We})}\,\mathrm{Re}^{0,05}. \tag{12}$$

Increase in heat transfer on account of waves at the lateral surface of the horizontal tube appear when Re > Re_v. In this case, isolating the wave zone with the boundary defined in Eq. (8) and taking account of the dependence of the characteristic of the wave conditions on Ka and Re, it is found that

$$\varepsilon_{v,s} = 0,01\,(\mathrm{Re}\,\mathrm{Ka}^{-1/11})^{1,2}\left(1-\frac{\theta_v}{\pi}\right). \tag{13}$$

Empirical values of the constants in Eq. (13) are found as a result of analyzing the experimental data of [3] (Khladon-12; T = 343 K; D = 0.012 m) by the given method using Eqs. (2), (3), (8), (12), and (13).

In Fig. 3 the results of calculation by the given method are compared with the available experimental data. The results obtained explain the difference in condensation rate of motionless vapor for materials with different Ka, We, and may be used to calculate the heat transfer in the condensation of pure motionless saturated vapor in the laminar-wave region.

NOTATION

ε, semiempirical coefficient; ρ, density; g, acceleration due to gravity; ν, kinematic viscosity; L, D, length and diameter of tube; $l_\nu = (\nu_1^2/g)^{1/3}$, $l_\sigma = (\sigma/\rho_1 g)^{1/2}$, viscous and capillary constants; l, δ, wavelength and thickness of the condensate layer, referred to l_σ; $k = 2\pi/l$, dimensionless wave number; ω, angular frequency, referred to $(g/l_\sigma)^{1/2}$; θ, angle measured from the upper point of the horizontal tube; λ, thermal conductivity; α, heat-transfer coefficient; $\mathrm{Nu}=\alpha l_\nu/\lambda$, $\mathrm{Re}=\pi Dq/r\rho_1\nu_1$, $\mathrm{We}=(l_\sigma/D)^2$, $\mathrm{Ka}=(l_\sigma/l_\nu)^6$, Pr, $K=r/c\Delta T$, Nusselt, Reynolds, Kapitsa, Prandtl, and Kutateladze numbers; Indices: N, Nusselt theory; t, taking account of the dependence of the thermophysical properties on the condensate temperature; i, characterizing the influence of convective acceleration; v, taking account of, or corresponding to, the presence of interphase surface waves; d, dominant wave; b, s, lower and lateral generatrices of tube surface; 1, liquid; 2, vapor.

LITERATURE CITED

1. S. S. Kutateladze, Fundamentals of Heat-Transfer Theory [in Russian], Moscow (1979).
2. D. A. Labuntsov, Teploénergetika, No. 7, 72-81 (1957).
3. I. I. Gogonin, A. R. Dorokhov, and V. I. Sosunov, Heat Transfer in Film Condensation of Motionless Vapor. Preprint 48-80 [in Russian], Institute of Thermophysics, Siberian Branch, Academy of Sciences of the USSR, Novosibirsk (1980).
4. V. M. Budov, V. A. Kir'yanov, and I. A. Shemagin, Izv. Akad. Nauk SSSR, Énerg. Transp., No. 6, 165-167 (1985).
5. V. M. Budov, V. A. Kir'yanov, and I. A. Shemagin, Izv. Akad. Nauk SSSR, Énerg. Transp., No. 3, 166-168 (1986).
6. Yang, Lorents, and Ganich, Teploperedacha, No. 1, 17-24 (1980).
7. I. I. Gogonin, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 10, Issue 2, 24-32 (1986).
8. I. I. Gogonin and V. I. Sosunov, Teor. Osn. Khim. Tekhnol., 18, No. 1, 56-61 (1984).