# EFFECT OF VAPOR VELOCITY ON HEAT TRANSFER DURING CONDENSATION

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UDC 536.247.536.423.1+04

An analysis of recently published results of an experimental investigation of heat transfer during film condensation of a moving vapor on a horizontal tube [1] confirms, as shown below, the previously noted [2, 3] divergence between the experimental and theoretical data for this case of condensation. The approximate theoretical formulas taking into account the tangential stresses on the liquid–vapor interface, and so, the heat-transfer coefficient as a function of the density of the transverse mass flow, can be used, however, as a first approximation in those cases when direct experimental data are absent.

The asymptotic solutions of the equations of motion for laminar and turbulent boundary layers with suction [4–7] lead to the following relation for shear stress on a longitudinally streamlined permeable plate:

$$\tau = jU \tag{1}$$

where j is the density of the transverse mass flow and U is the velocity of the medium beyond the limits of the boundary layer.

If we assume that during film condensation of a moving saturated vapor the shear stress on the phase interface is determined by Eq. (1), we can obtain [2, 3, 8]

$$\frac{\alpha}{\alpha_s} = f\left(\frac{F}{PK}\right) \tag{2}$$

Here $\alpha$ and $\alpha_s$ are the heat-transfer coefficients during condensation of moving and stationary vapor; $F = U^2/(gl)$ is the Froude number for the vapor flow; $P = \nu\rho c_p/\lambda$ is the Prandtl number of the condensate; $K = r/(c_p\vartheta)$ is the phase transition number; g is the acceleration of gravity; $l$ is a characteristic dimension (height for a vertical surface and outside diameter for a horizontal tube); $\nu$, $\lambda$, $c_p$, $\rho$ are the coefficient of kinematic viscosity, coefficient of heat conductivity, specific heat, and density of the condensate; r is the heat of condensation; $\vartheta$ is the vapor–wall mean temperature difference.

Equation (1) does not satisfy the limiting conditions $\tau \to \tau_d$ when $j \to 0$ (where $\tau_d$ is the shear stress of "dry" friction in the absence of a transverse mass flow). But during condensation of a moving pure vapor the value of j is generally relatively large and remains large also when $U \to 0$.

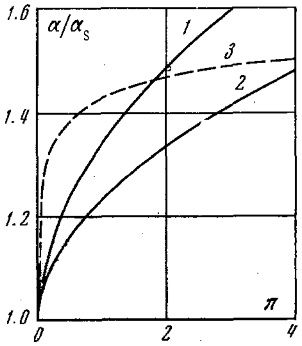


Fig. 1

The numerical solution of the problem of heat transfer during film condensation of moving vapor on a vertical surface (flat plate or surface of small curvature) proposed by Nusselt [9] was based on the assumption that $\tau = \tau_d$, i.e., did not take into account the effect of the transverse mass flow on shear stress. However, when determining $\tau$ by means of Eq. (1) we can use the results of this numerical solution if in the complex

$$\Pi_N = \tau \frac{\alpha_s}{\lambda\rho g} = c_f \frac{U^2\rho''}{2} \frac{\alpha_s}{\lambda\rho g} \tag{3}$$

where $c_f$ is the frictional resistance coefficient and $\rho$ is the vapor density, we replace $\tau$, i.e., use instead of $\Pi_N$ the modified complex

$$\Pi_N^* = jU \frac{\alpha_s}{\lambda\rho g} = \frac{\alpha\vartheta}{r} \frac{U\alpha_s}{\lambda\rho g} \tag{4}$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 184–187, November-December, 1971. Original article submitted June 16, 1971.

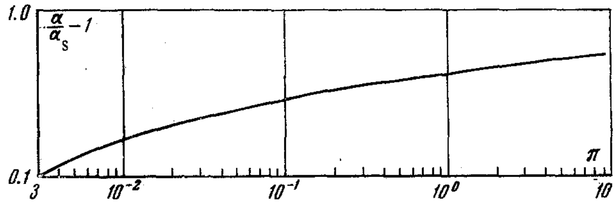


Fig. 2

The relation thus obtained for the heat-transfer coefficient in the case of a descending vapor flow is described nicely by the equation [3]

$$\frac{\alpha}{\alpha_s} = 0.125\left(\sqrt{\Pi+16}+2\sqrt{\Pi}\right)\left(\sqrt{\Pi+16}-\sqrt{\Pi}\right)^{0.5} \tag{5}$$

where

$$\Pi = F/(PK)$$

For condensation on a transversely streamlined horizontal tube the equation [2]

$$\left(\frac{\alpha}{\alpha_s}\right)^{-4} + 0.79\,\Pi^{0.5}\left(\frac{\alpha}{\alpha_s}\right)^{-8/3} - 1 = 0 \tag{6}$$

was obtained by approximate solution.

The relations described by Eqs. (5) and (6) can be approximated for the range of values $\alpha/\alpha_s \le 1.6$ with sufficient accuracy by the simple equation [8]

$$\alpha/\alpha_s = 1 + a\Pi^{0.5} \tag{7}$$

where for a vertical surface $a = 0.345$ (curve 1 in Fig. 1) and for a horizontal tube $a = 0.24$ (curve 2 in Fig. 1).

Since the available experimental data for the condensation conditions being considered are still few and cover only narrow regions of the change of the main parameters of the process, it was suggested to use Eqs. (5)-(7) for an approximate evaluation of the effect of vapor velocity on the heat-transfer coefficient in those cases when experimental data are absent [8]. The reference here was to the fact that the additional effects not taken into account by these equations, mainly the possibility of disturbance of the laminar flow regime of the liquid film under the effect of perturbations caused by the vapor flow, should lead to an increase of the intensity of heat transport across the film, i.e., the practical use of the indicated equations cannot lead to an insufficient value of the required heat-transfer area. Here it was stipulated that the form of Eq. (2) for different conditions requires correction as new theoretical and experimental data appear. In this connection it is of interest to examine the results of an experimental investigation of the condensation of moving Freon-21 vapor on a horizontal tube described in [1].

On the basis of determining the shear stress $\tau$ by means of Eq. (1), the authors of [1] plotted their experimental values of $\alpha/\alpha_s$ as a function of the product of $\pi_1\pi_2$, where

$$\pi_1 = \frac{v}{U}, \qquad \pi_2 = \frac{U^2\rho''\alpha_s}{\lambda\rho g}$$

Here v is the linear velocity of the transverse flow.

Substituting the indicated values of the parameters $\pi_1$ and $\pi_2$, we obtain that

$$\pi_1\pi_2 = \frac{v}{U}\,\frac{U^2\rho''\alpha_s}{\lambda\rho g} = \frac{\alpha\vartheta}{r}\,\frac{U\alpha_s}{\lambda\rho g} = \Pi_N^*$$

The authors of [1] presented the experimental results only in a graphic form, but the averaging curve (straight line in semilogarithmic coordinates) plotted by them through the experimental points can be described by the equation

$$\alpha/\alpha_s = 1.46 + 0.104\ln\Pi_N^* \tag{8}$$

A dependence of the form $\alpha/\alpha_s = f(\Pi_N{*})$ is inconvenient since the argument $\Pi_N{*}$ includes the heat-transfer coefficient $\alpha$ being determined. To obtain a more clear-cut and convenient dependence of the heat-transfer coefficient on the vapor velocity, we will transform Eq. (8).

For condensation on a horizontal tube the parameter $\Pi_N{*}$ can be represented as

$$\Pi_N{}^{*} = 0.526 \frac{\alpha}{\alpha_s} \Pi \tag{9}$$

where $\Pi$ is the complex figuring in Eq. (5). Then from (8) and (9) we obtain

$$\frac{\exp[9.62(\alpha/\alpha_s - 1)]}{0.526\,\alpha/\alpha_s} = \Pi^{0.5} \tag{10}$$

Equation (10) is presented in a graphic form in Fig. 1 (curve 3) and in log-log coordinates in Fig. 2. If we replace the curve in Fig. 2 by a broken line with a break at $\Pi = 0.1$, then with deviations from its corresponding values of $\alpha/\alpha_s$ of not more than $\pm 1.5\%$ we can represent this dependence in the form

$$\begin{aligned} \alpha/\alpha_s &= 1 + 0.62\,\Pi^{0.3} \quad \text{when } 0.003 \leqslant \Pi \leqslant 0.1 \\ \alpha/\alpha_s &= 1 + 0.42\,\Pi^{0.13} \quad \text{when } 1.0 \leqslant \Pi \leqslant 9 \end{aligned} \tag{11}$$

As follows from a comparison of curves 2 and 3 in Fig. 1 and from Eqs. (7) and (11), the experimental data of [1] for condensation of Freon-21 vapor agree well with the previously published analogous experimental data of the All-Union Institute of Heat Engineering [10] for condensation of water vapor. In the region of comparatively small $\Pi$ they demonstrated a considerably greater increase of the heat-transfer coefficient with increase of vapor velocity than in the theoretical calculations, which suggest a purely laminar flow of the condensate and take into account the effect of shear stress $\tau$ only on the thickness of the laminar condensate film.

The experimental data considered confirm the presence of additional effects intensifying heat transport across the condensate film. An additional increase of the heat-transfer coefficient can be caused by a shift in the presence of condensation of the point of separation of the boundary layer from the surface of the cylinder in the direction of the larger polar angle reckoned from the front critical point and by disturbance of the purely laminar flow regime of the condensate film with its transition to a laminar-wave regime. These experimental data confirm also the validity of using Eqs. (5)-(7) in calculations for conditions not covered by experimental investigations, which permit evaluating the effect of vapor velocity on the heat-transfer coefficient with some reduction.

## LITERATURE CITED


1. I. I. Gogonin and A. R. Dorokhov, "Heat transfer during condensation of moving Freon-21 vapor on a horizontal tube," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 2, 129-133 (1971).
2. L. D. Berman, "Heat transfer during film condensation of a moving vapor," Teploénergetika, No. 7, 56-61 (1966).
3. L. D. Berman, "Calculated and experimental data for the coefficient of heat transfer during condensation of moving vapor," Tr. Tsent. Nauch.-Issled. i Proektno-Konstrukt. Kotloturb.Inst., No. 101, 262-272 (1970).
4. H. Schlichting, Boundary Layer Theory, McGraw-Hill (1960).
5. S. S. Kutateladze and A. I. Leont'ev, Turbulent Boundary Layer of a Compressible Gas [in Russian], Izd. SO AN SSSR, Novosibirsk (1962).
6. S. S. Kutateladze, Principles of Heat-Transfer Theory [in Russian], Nauka, Novosibirsk (1970).
7. R. S. Silver, "An approach to a general theory of surface condensers," Proc. Instn. Mech. Engrs., 178, No. 1, 339-357 (1964).
8. L. D. Berman, "Heat transfer during film condensation of a moving vapor on a vertical surface and horizontal tube," in: Proceedings of the Fourth All-Union Conference on Heat Transfer and Hydraulic Resistances during Movement of a Two-Phase Flow in Elements of Power Machines and Apparatuses [in Russian], Part 1, Leningrad (1971), pp. 29-32.
9. W. Nusselt, "Die Oberflächenkondensation des Wasserdampfes," Zeitschr. d. Verein Deutscher Ingenieure, 60, No. 28, 569 (1916).
10. L. D. Berman and Yu. A. Tumanov, "Investigation of heat transfer during condensation of moving vapor on a horizontal tube," Teploénergetika, No. 10, 77-83 (1962).