ANALYSIS OF HEAT EXCHANGE IN FILM CONDENSATION OF STATIONARY VAPOR ON A VERTICAL SURFACE

S. S. Kutateladze, I. I. Gogonin, and N. I. Grigor'eva

UDC 536.248.2

The article presents an analysis of the theoretical and experimental data on heat exchange with vapor condensation on a vertical surface, and it demonstrates the calculation of the heat transfer coefficients taking the transient zone of the flow into account.

In addition to the purely empirical dependences [1, 2], the following approaches are used at present for describing the heat exchange by condensation in a turbulent falling film:

1) analogy of heat transfer and momentum [3, 4];

2) numerical integration of the differential equations of motion and energy with specified empirical or semiempirical coefficients of turbulent momentum and heat transfer, sometimes with subsequent approximation of the calculation results by criterial equations [5-8];

3) approximate analytical solutions [9].

Table 1 contains the principal dependences suggested for describing heat exchange in turbulent flow of a film of condensate on a vertical surface.

A feature common to all these works is the application of the regularities of turbulent flow in a pipe to flow in a film. Thus, in the works using the first approach, the description of heat exchange in turbulent falling film is based on the following initial dependences:

$$\mathrm{Nu} = \xi \mathrm{Re}^{l} \mathrm{Pr}^{m}, \tag{1}$$

$$\xi = A\,\mathrm{Re}^{-n}. \tag{2}$$

It is usual to adopt the values n = 0.20-0.25, $l \approx 0.8$, and m = 0.3-0.4, with the proportionality factor being specified according to data on flow in smooth pipes. Usually, the hydraulic diameter is put equal to four times the thickness of the film.

Most authors using the second approach assume that the distribution of friction across the thickness of the film is linear:

$$\tau = g(\rho' - \rho'')(\delta - y), \tag{3}$$

where

$$\tau = (\mu + \mu_{\text{т}}) \frac{\partial u}{\partial y}. \tag{4}$$

Domanskii and Sokolov [8] assume that friction across the thickness of the film is constant and equal to the friction on the wall. The equation of temperature distribution in the film is written in the form

$$q = -(\lambda + \lambda_{\text{т}}) \frac{\partial T}{\partial y}, \tag{5}$$

where the heat flux q is usually considered constant and equal to the flow on a solid wall.

The relation

$$\mathrm{Re} = \int_0^{\eta_\delta} \varphi\, d\eta \tag{6}$$

Thermophysical Institute, Siberian Branch, Academy of Sciences of the USSR, Novosibirsk.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 44, No. 6, pp. 885-894, June, 1983. Original article submitted March 11, 1982.

TABLE 1. Dependences for Calculating Heat Transfer in Condensation of Stationary Vapor on Vertical Surfaces in Turbulent Falling Film

Literature	Formula	Re; Re_{cr}
Kirkbride [1]	$Nu^* = 0{,}0076\,Re^{0,4}$	$Re = 4G/\nu$; $Re_{wa} = 2000$
Colburn [3]	$Nu^* = Re/[22Pr^{-1/3}(Re^{0,8} - 364) + 12800]$	$Re = 4G/\nu$; $Re_{wa} = 1600$
Kutateladze [5]	$Nu^* = 0{,}4Pr\eta_\delta^{1/3}\left(\ln\frac{\sqrt{\eta_\delta}+\sqrt{\eta_\delta - 11{,}6}}{\sqrt{\eta_\delta}-\sqrt{\eta_\delta - 11{,}6}} + 4{,}65\,Pr\right)^{-1}$, $Re = \eta_\delta(3{,}0 + 2{,}5\ln\eta_\delta) - 39$	$Re = G/\nu$; $Re_{wa} = 100$
Grigull [2]	$Nu^* = 2{,}08\cdot 10^{-2}\,Re^{1/3}$	$Re = G/\nu$; $Re_{wa} = 270$
Labuntsov [6]	$Nu^* = Re/[2300 + 41Pr^{-0,5}(Re^{3/4} - 89)\,(Pr/Pr_{wa})^{-0,25}]$	$Re = G/\nu$; $Re_{wa} = 400$
Gudymchuk, Konstantinov [4]	$Nu^* = Re/[21{,}6Pr^{-0,3}(Re^{0,78} - 323) + 12740]$	$Re = 4G/\nu$; $Re_{wa} = 1600$
Dukler [7]	Numerical solution	$Re = G/\nu$; $Re_{wa} = 115$
Domanskii, Sokolov [8]	$Nu^* = Pr\eta_\delta^{1/3}/[5Pr + 5\ln(1 + 5Pr) + 2{,}5\ln\frac{1 - Pr + 0{,}4Pr\eta_\delta}{1 + 11Pr}]$, $Re = \eta_\delta(3{,}0 + 2{,}5\ln\eta_\delta) - 64$	$Re = G/\nu$; $Re_{wa} = 280$
Levin, Brdlik [9]	$Nu^* = 0{,}173 + (0{,}22Pr^{1/3} - 0{,}173)\frac{Re - 400}{Re}$	$Re = G/\nu$; $Re_{wa} = 400$

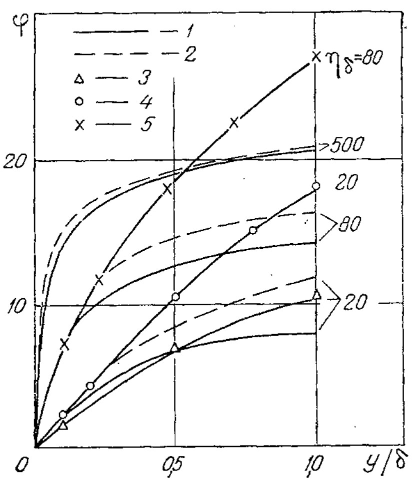

Fig. 1. Comparison of calculated and measured velocity profiles in films: 1) calculation after [7]; 2) [8]; 3) measurements after [10]; 4) [12]; 5) [11]. $\varphi = U/\sqrt{\frac{\tau_{wa}}{\rho}}$; $y/\delta = \eta/\eta_\delta$.

serves for determining the thickness of the film. It is also assumed that turbulent viscosity and thermal diffusivity are equal, i.e., that the turbulent Prandtl number $Pr_T = 1$.

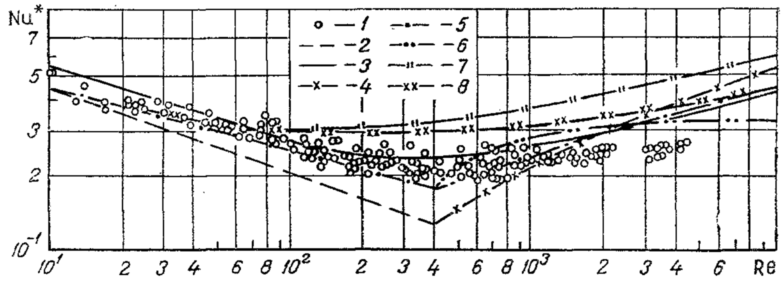

Fig. 2. Dependence of the Nusselt number on the Reynolds number as calculated by different authors (Pr = 3.5): 1) [15]; 2) [14]; 3) [5]; 4) [3]; 5) [6]; 6) [9]; 7) [8]; 8) [7].

The principle differences of the works using the second approach concern the following tenets.

In [5, 8] the velocity profile is assumed to be specified (in the laminar sublayer it is linear, in the remaining region logarithmic). In [6, 7] the velocity profile and the thickness of the film are found from the joint solution of Eqs. (3), (4), and (6).

In Fig. 1, which presents the velocity profiles for the same dimensionless film thickness, calculated after [7, 8] and compared with the experimental data of [10-12], we can see that the calculations and measurements do not agree well with each other.

For the coefficients of turbulent transfer, various dependences containing empirical constants are being chosen. For instance, Dukler [7] uses Deisler's relation in the region near the solid wall ($\eta < 20$) for ν_T and a_T, and Karman's relationship for the remaining region. Kutateladze [5] adopts the following expressions (Prandtl's two-layer model) for turbulent viscosity: for $0<y<11.6\nu/U_{wa}$ $\mu_T=0$, $U_{wa}=\sqrt{\tau_{wa}/\rho}$, for $y>11.6\nu/U_{wa}$ $\mu_T=0.16\rho' y^2 \frac{du}{dy}$. Labuntsov [6] uses two variants of multilayer schemes (after Lin and Schlinger).

If different expressions are specified for the coefficient of viscosity and the velocity profiles in different regions over the section of the film, it leads to different expressions of the values of the critical Reynolds number (see Table 1). For instance, according to Dukler, the value $\eta = 20$ corresponds to $Re_{cr} = 115$. In [8] the chosen boundary of the zone yields $Re_{cr} = 280$. Kutateladze [5] adopts the critical Reynolds number $Re_{cr} = 100$.

The third approach is used in [12] with the following assumptions.

1. To describe the friction stresses on the wall, Brauer's experimental dependence [13] is adopted.

2. It is assumed that the thickness of the film and the velocity on the phase interface change exponentially with the same exponent equal to 1/2. The authors emphasize that the consequence is that the heat transfer coefficient in turbulent flow of condensate on an isothermal surface remains constant.

3. The critical Reynolds number Re_{cr} and the Nusselt number calculated for $Re = Re_{cr}$ are taken to be constant and not dependent on the physical properties of the liquids.

4. The transition from subcritical to turbulent flow and the corresponding change of the heat transfer coefficients occur by a jump.

It must be pointed out that a characteristic feature of all the works is that the mean heat transfer coefficient over the length of the film in mixed flow is determined solely according to laminar and turbulent flow:

$$\langle Nu^* \rangle = \langle Nu_l^* \rangle \frac{Re_{cr}}{Re} + \langle Nu_T^* \rangle \frac{Re - Re_{cr}}{Re},$$

whereas in experiments the existence of an extended transient region is observed, where the heat exchange is practically independent of the Reynolds number of the film.

Figure 2 presents the results of calculations of the mean Nusselt number according to models recommended by different authors, and these are compared with the experimental data on the condensation of Chladone-21 in [15].

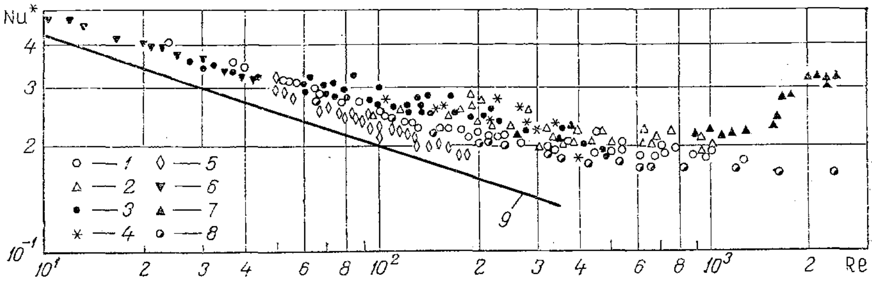

Fig. 3. Experimental data on heat exchange in the condensation of water vapor on vertical pipes (Pr = 1.75): 1) [24] (Re = 24 – 1260); 2) [26] (Re = 115 – 1000); 3) [22] (Re = 27 – 490); 4) [21] (Re = 110 – 435); 5) [23] (Re = 50 – 180); 6) [25] (Re = 2.5 – 44); 7) [27] (Re = 275 – 2370); Pr = 1.1; 8) [24] (Re = 68 – 2340); 9) calculation after [14].

Calculations according to Dukler's model, presented in these figures, were carried out by us on the assumption that there is no interphase friction, by our own program for Prandtl numbers for which experimental data are available. Our calculations agree with similar results obtained by Dukler in his original work [7].

It can be seen from Fig. 2 that the divergence in the analytical dependences of $\langle Nu^* \rangle$ on Re obtained by different authors occurs both in the transient and in the turbulent zones of falling film. All these calculations differ noticeably from the experimental data on the condensation of Chladone-21 [15]. The model of Domanskii and Sokolov [8] obtains much higher Nusselt numbers than other calculations, apparently because, in distinction to most other authors, friction over the section of the film was considered constant and equal to the friction with the wall. Such an assumption leads to the following equation for the temperature:

$$\frac{d\theta}{d\eta} = \frac{1}{1/\mathrm{Pr} - 1 + 1/\dfrac{d\varphi}{d\eta}}. \tag{7}$$

For linear distribution of friction, which describes flow in a film more accurately, the corresponding equation has the form

$$\frac{d\theta}{d\eta} = \frac{1}{1/\mathrm{Pr} - 1 + 1/\dfrac{d\varphi}{d\eta} - \eta/\eta_\delta \cdot 1/\dfrac{d\varphi}{d\eta}}. \tag{8}$$

This equation is examined, in particular, in Dukler's scheme [7]. The difference between the velocity profiles after Dukler and [8] is shown in Fig. 1. The difference of the temperature profiles in [8], and consequently also of the Nusselt numbers, is due, in addition to the derivative of the velocity, as can be seen from Eqs. (7) and (8), also to the fact that Eq. (7) does not contain the term $\eta/\eta_\delta \cdot 1/(d\varphi/d\eta)$. The numerical solution of the equation for the temperature, carried out by us without this term but by using the velocity profile calculated after Dukler, leads to a dependence of $\langle Nu^* \rangle$ on Re which practically does not differ from the dependence in [8]. It follows from this that the high Nusselt numbers in the scheme of [8] are due principally to the introduction of the assumption that friction over the section of the film is constant.

The results of the calculations by the dependence of Domanskii and Sokolov were compared by these authors only with their own measurements of heat exchange in the evaporation of films of liquids with substantially differing Prandtl numbers (Pr = 1.75-29.5). However, Struve [16] showed that these experiments differ noticeably (by up to 80%) from the experimental data obtained by other authors.

It may be noted that the experimental data on heat exchange in the condensation of Kh-21 [15], Kh-12 [17, 18], and carbon tetrachloride [19] agree well with Struve's experiments with the evaporation of Chladone-11 carried out in the range Re 20-2000 and with approximately the same Prandtl numbers as in the experiments with condensation. The experiments using different methods in the investigation of condensation and evaporation agree satisfactorily with each other, and according to them, we can confidently evaluate the reliability of the theoretical calculations.† In addition, this means that the existing self-similarity of heat exchange upon change of the specific flow rate within wide limits may be viewed as a general regularity in the heat exchange of falling films on a vertical surface, regardless of the direction of the heat flux. An analysis of this phenomenon and a quantitative evaluation of the heat exchange in the self-similarity region were carried out in [20].

Figure 3 presents the results of experiments by various authors, obtained with the condensation of water vapor [21-26]; these results agree satisfactorily with each other. Kutateladze and Shrentsel' [24] carried out their experiments with pipes 0.5 to 4 m long, at saturation temperatures of 95-152°C; this made it possible to change the Prandtl number from 1.87 to 1.14.

An exception among the presented experimental results are the data of [27] for $Re > 1400$; this is apparently due to the particular method of arranging deposition that was used by the authors to obtain large Reynolds numbers of the film. The results obtained in this work for $Re \approx 2 \cdot 10^3$ are noticeably higher than the data of the previously quoted works on the condensation of refrigerants, although the Prandtl numbers of these refrigerants were twice as large.

The analytical dependences in the range of high Reynolds numbers concerning condensation of stationary vapor are usually compared with the experimental data on the condensation of diphenyl vapors [28]. However, it must be pointed out that the experiments of Badger et al. were carried out on pilot plant equipment, and this led to great scatter of the data. With the highest Reynolds numbers of the film in these experiments ($Re \approx 7600$), the velocity of the vapor at the inlet to the slit channel formed by the jacket and the segment attained 6 m/sec at a vapor density $\rho'' = 5$ kg/m^3. Our evaluations showed that such a velocity of the vapor could lead to a doubling of the intensity of heat exchange in the upper part of the pipe. Moreover, this velocity might have led to the stripping of the wave crests, their fragmentation, and subsequent falling of the liquid, not down the experimental pipe, but along the jacket, because the fragmentation criterion determined according to [29, 30] was more than twice as large as the critical value. Therefore, the results of experiments in this work cannot be considered without taking into account the effect of the vapor velocity, and they cannot be compared with the theoretical dependences describing the heat exchange of stationary vapor.

It follows from the above data that in the transient region of falling film, the differences between the theoretical and experimental dependences manifest themselves most clearly and attain as much as 200%. One of the causes of such divergence is the ambiguity in selecting the critical Reynolds number Re_{cr}. A substantial cause of the divergence of the calculations from the experimental data is also the exclusion of an extensive transient zone of film flow from the calculation schemes. A comparison of experiments and theoretical dependences shows that in the turbulent region of film flow with $Re > 10^3$ the mean $\langle Nu^* \rangle$ number depends on the Reynolds number much more weakly than the calculated manner. There are no reliable experimental data for the developed turbulent range of falling film ($Re > 5 \cdot 10^3$). The literature also lacks experiments carried out with large Prandtl numbers within a wide range of change of Reynolds numbers of the film. The conclusion is that it is useful to use the following procedure for calculating heat exchange in condensation with mixed flow regime.

The mean Nusselt numbers are calculated by the formula

$$\langle Nu^* \rangle = \langle Nu_l^* \rangle \frac{Re_{lw}}{Re} + \langle Nu_w^* \rangle \frac{Re_{cr} - Re_{lw}}{Re} + \langle Nu_\tau^* \rangle \frac{Re - Re_{cr}}{Re}.$$

Here $\langle Nu_l^* \rangle = 4/3(3Re)^{-1/3}$. The boundaries of the laminar-wavy range (Re_{lw}, Re_{cr}), and also the Nusselt numbers $\langle Nu_w^* \rangle$, are determined analogously to [20] on the basis of the fact that the "residual" thickness of the film in dependence on the Reynolds number is constant.

According to [13], laminar flow changes into laminar-wavy flow when

$$Re_{lw} = 2.3\, Ar_*^{1/5}, \tag{9}$$

†The data of [16-19] are not contained in Fig. 2 so as not to clutter up the figure.

TABLE 2. Nusselt Numbers $\langle Nu_T^* \rangle$ Calculated by Formulas (11)-(13)

Pr	η_δ: 60	100	200	300	1000	4000
	Re: 742	1516	3697	6047	24244	112432
1	0,157	0,160	0,168	0,176	0,213	0,285
2	0,212	0,223	0,245	0,262	0,332	0,452
3	0,252	0,270	0,300	0,324	0,416	0,572
5	0,307	0,332	0,377	0,410	0,532	0,735
7	0,344	0,374	0,428	0,467	0,607	0,841
10	0,382	0,418	0,479	0,523	0,682	0,948

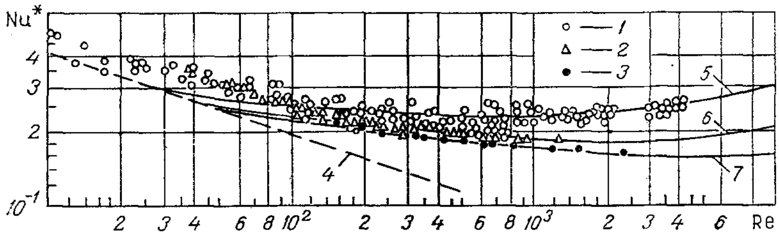

Fig. 4. Comparison of the experimental data with calculation by the suggested procedure: 1) condensation of Chladone-21 [15] (Pr = 3.4; Re = 10-4250); 2) condensation of water vapor [24] (Pr = 1.75; Re = 25-1260); 3) condensation of water vapor [24] (Pr = 1.14; Re = 65-2340); 4) calculation after Nusselt; 5, 6, 7) calculation by the present authors for Pr = 3.4, 1.75, and 1.14, respectively.

and laminar-wavy flow changes into turbulent-wavy flow when

$$Re_{cr} = 35\,Ar_*^{1/5}. \qquad (10)$$

For Re $\leqslant Re_{lw}$, the mean thickness of the film and the residual thickness coincide and can be determined by Nusselt's formula. In the laminar-wavy range ($Re_{lw} \leqslant Re \leqslant Re_{cr}$) the residual thickness does not depend on Re, and consequently it is also determined by Nusselt's formula for Re = Re_{lw}, i.e., $\delta_{res} = (Re_{lw})^{1/3}(3\nu^2/g)^{1/3}$. In that case $\alpha_w = \lambda/\delta_{res}$ and $\langle Nu_{lw}^* \rangle (\alpha_w/\lambda) \times (\nu^2/g)^{1/3} = (3Re_{lw})^{-1/3}$. As regards the determination of Nusselt numbers for turbulent flow ($\langle Nu_T^* \rangle$), the following must be pointed out. In the case of heat exchange without phase transition, when the heat flux changes from zero on the surface of the film to the maximum value at the wall, transfer in the viscous sublayer is decisive. In condensation, however, the distribution of the heat flux across the section of the film is almost uniform, and therefore the mechanism of turbulent transfer over the entire section of the film are of substantial importance.

For a more detailed description of the mechanism of turbulent transfer, we will examine a model in which turbulent viscosity is approached piecewise by the dependences

$$\begin{gathered} 0<\eta<6.8,\ \bar{\mu}_T=0;\ 6.8<\eta<0.2(\eta_\delta-6.8), \\ \bar{\mu}_T=0.4(\eta-6.8)\sqrt{1-\eta/\eta_\delta};\ 0.2(\eta_\delta-6.8)<\eta<\eta_\delta, \\ \bar{\mu}_T=0.08(\eta-6.8)\sqrt{1-\eta/\eta_\delta}. \end{gathered} \qquad (11)$$

In this model, the length of the path of displacement outside the viscous sublayer is subtracted from its conventional boundary $\eta = 6.8$ correlating with the value of the Prandtl–Karman constant $\varkappa = 0.4$. The dimensionless thickness of the film is correlated with the Reynolds number by the following dependence, obtained on the assumption that friction over the section of the film is linearly distributed:

$$\mathrm{Re} = \frac{1}{\eta_\delta}\int_0^{\eta_\delta}\varphi(\eta)\,d\eta = \frac{1}{\eta_\delta}\int_0^{\eta_\delta}\left(\int_0^{\eta}\frac{\eta_\delta-\eta}{1+\mu_T(\eta)}d\eta\right)d\eta = \frac{1}{\eta_\delta}\int_0^{\eta_\delta}\frac{(\eta_\delta-\eta)^2}{1+\bar{\mu}_T(\eta)}d\eta. \quad (12)$$

The local and mean Nusselt numbers are calculated by the relations

$$\mathrm{Nu}_T^* = \eta_\delta^{1/3}\left(\int_0^{\eta_\delta}\frac{d\eta}{1+\mathrm{Pr}\bar{\mu}_T}\right)^{-1};\quad \langle \mathrm{Nu}_T^* \rangle = (\eta_\delta - \eta_{\delta_{cr}})^{-1}\int_{\eta_{\delta_{cr}}}^{\eta_\delta}\mathrm{Nu}_T^* d\eta_\delta. \quad (13)$$

Table 2 presents the results of numerical calculation by formulas (11)-(13) for some integers as Prandtl numbers.

Figure 4 shows a comparison between the dependence $\langle \mathrm{Nu}^* \rangle$ calculated by the described procedure and the experimental data. It can be seen that the calculations agree well with the experimental data.

It should be pointed out that the Reynolds numbers Re_{lw} and Re_{cr}, determined by (9) and (10), are functions of the Archimedes number, and they noticeably differ from each other for different liquids and different saturation temperatures. Numerical calculation with these values of Re_{lw} and Re_{cr} leads to qualitatively correct conformity of the theoretical lines 5-7 with the experimental results, where for $\mathrm{Re} > \mathrm{Re}_{lw}$ the experimental data slightly but distinctly diverge for different substances.

Thus, in mixed falling of a film, satisfactory results are obtained from calculating the heat transfer coefficient if heat exchange in the laminar-wavy range is determined from the "residual" thickness of the film, and if in turbulent fall it is determined by the suggested model.

NOTATION

$\mathrm{Nu} = \frac{\alpha D}{\lambda}$; $\mathrm{Nu}^* = \frac{\alpha}{\lambda}\left(\frac{\nu^2}{g}\right)^{1/3}$, Nusselt number; Re, Reynolds number; Pr, Prandtl number; ρ', density of the liquid; ρ'', density of the vapor; δ, thickness of the film; g, acceleration of gravity; q, heat flux; λ, thermal conductivity; U, velocity of flow; T, temperature; μ, dynamic viscosity; $\eta = \frac{\sqrt{\tau_{wa}/\rho'}}{\nu}y$, dimensionless coordinate; η_δ, dimensionless thickness of the film ($y = \delta$); ν, kinematic viscosity; a, thermal diffusivity; α, heat-transfer coefficient; x, coordinate along the surface; y, coordinate across the film; $\varphi = U/\sqrt{\tau_{wa}/\rho'}$, dimensionless velocity; $\theta = [C_p(T_{wa} - T)\sqrt{\tau_{wa}/\rho}]/q_{wa}$, dimensionless temperature; C_p, heat capacity; $\mathrm{Ar}_* = (\sigma^3/\nu^4\rho^3 g)^{1/2}$, Archimedes number. Subscripts: wa, wall; T, turbulent; cr, critical; $\langle\ \rangle$, mean lengthwise.

LITERATURE CITED

1. C. G. Kirkbride, "Heat transfer by condensing vapor on vertical tubes," Ind. Eng. Chem., 26, No. 4, 425-428 (1934).
2. G. Greber, S. Erk, and G. Grigull, Fundamentals of Heat Exchange [Russian translation], Inostr. Lit., Moscow (1958).
3. A. P. Colburn, "Calculation of condensation with a portion of condensate layer in turbulent motion," Ind. Eng. Chem., 26, No. 4, 432-434 (1934).
4. V. A. Gudymchuk and V. A. Konstantinov, "Heat transfer in vapor condensation on a solid surface," Zh. Tekh. Fiz., 6, No. 9, 1582-1587 (1936).
5. S. S. Kutateladze, Foundations of the Theory of Heat Exchange [in Russian], Atomizdat, Moscow (1979).
6. D. A. Labuntsov, "Heat transfer in film condensation of pure vapors on vertical and horizontal pipes," Teploenergetika, No. 7, 72-80 (1957).
7. A. E. Dukler, "Dynamics of vertical falling film systems," Chem. Eng. Progr., 55, No. 10, 62-67 (1959).
8. I. V. Domanskii and V. N. Sokolov, "Heat transfer to a falling film of liquid previously heated to boiling point," Zh. Prikl. Khim., 40, No. 1, 66-71 (1967).
9. A. B. Levin and I. P. Brdlik, "Heat transfer in turbulent flow of condensate film," in: Problems of Heat Transfer. Materials of a Scientific Seminar, MLTI, Moscow (1976), pp. 107-115.

10. R. A. Cook and R. R. Clark, "The experimental determination of velocity profiles in smooth falling of liquid films," Can. J. Chem. Eng., 49, 412-416 (1971).
11. T. Ueda and H. Tanaka, "Measurements of velocity, temperature and velocity fluctuation distributions in falling liquid films," Int. J. Multiphase Flow, 2, 261-272 (1975).
12. F. C. K. Ho and R. L. Hammel, "Average velocity distributions within falling liquid film," Chem. Eng. Sci., 25, 1225-1237 (1970).
13. H. Brauer, "Strömung und Wärmeübergang bei Reiselfilmen," VDI Forschungs, No. 457, 1-140 (1956).
14. W. Nusselt, "Die Oberflächenkondensation des Wasserdampfes," Z. VDI, 60, 541-546, 568-575 (1916).
15. I. I. Gogonin, A. V. Dorokhov, and V. I. Sosunov, "Heat exchange in film condensation of stationary vapor on a vertical surface," Inzh.-Fiz., 35, No. 6, 1050 (1978).
16. H. Struve, "Der Wärmeübergang an einen verdampfenden Reiselfilm," VDI-Forschungs, No. 534, 5-36 (1969).
17. I. V. Mazyukevich, "Investigation of heat exchange in the condensation of the vapors of some refrigerants," in: Problems of Heat Exchange upon Change of the State of Aggregation of a Substance, GÉI, Moscow—Leningrad (1953), pp. 56-80.
18. I. v. D. Walt and D. G. Kröger, "Heat transfer during film condensation of saturated and superheated Freon-12," Progr. Heat Mass Transfer, 6, 79-98 (1973).
19. N. V. Zozulya and Yu. G. Khorunzhii, "Heat transfer in condensation of carbon tetrachloride vapor on a vertical pipe," in: Heat Transfer on Change of State of Aggregation of a Substance [in Russian], Naukova Dumka, Kiev (1964), pp. 85-89.
20. S. S. Kutateladze, I. I. Gogonin, N. I. Grigor'eva, and A. V. Dorokhov, "Determination of the heat transfer coefficient in film condensation of stationary vapor on a vertical surface," Teploenergetika, No. 4, 5-7 (1980).
21. A. I. Butuzov, V. G. Rifert, and G. G. Leont'ev, "Experimental investigation of the heat exchange in vapor condensation on vertical pipes with wire finning," in: Thermophysics and Heat Engineering [in Russian], No. 24, Naukova Dumka, Kiev (1973), pp. 94-96.
22. N. V. Zozulya, "Investigation of heat transfer in vapor condensation on vertical pipes," in: Heat Transfer and Thermal Modeling [in Russian], M. A. Mikheev (ed.), Moscow (1959), pp. 287-297.
23. Yu. G. Burov, "Heat exchange in water vapor condensation on vertical pipes," Zh. Tekh. Fiz., 27, No. 2, 331-337 (1957).
24. S. S. Kutateladze and A. N. Shrentsel', "Formulas and graphs for calculations of the overall heat transfer coefficient in vertical preheaters with film condensation of slowly moving saturated steam," Sovetskoe Kotloturbostr., No. 4, 149-152 (1938).
25. G. V. Ratiani and I. G. Sherkiladze, "Experimental investigation of the regularities of heat exchange in the transition from laminar film flow to wavy flow," Teploenergetika, No. 3, 78-80 (1964).
26. S. J. Meisenburg, R. M. Boarts, and W. L. Badger, "The influence of small concentrations of air in steam film coefficient of heat transfer," Trans. AIChE, 31, 622-638 (1934-1935).
27. V. A. Gudemchuk, "Heat exchange in vapor condensation on a vertical pipe," Izv. VTI, No. 6, 29-32 (1946).
28. W. L. Badger, C. C. Monrad, and H. W. Diamond, "Evaporation of caustic soda to high concentration by means of diphenyl vapors," Ind. Eng. Chem., 22, No. 7, 700-707 (1930).
29. M. S. Volynskii, "Fragmentation of drops in an air stream," Dokl. Akad. Nauk SSSR, 62, No. 3, 301 (1948).
30. A. A. Borisov, B. E. Gel'fand, M. S. Natanzon, and O. M. Kossov, "Fragmentation regimes of drops and criteria of their existance," Inzh.-Fiz. Zh., 40, No. 1, 64-70 (1981).