CONDENSATION OF A VAPOR MIXTURE IN THE ABSENCE OF NONCONDENSING GASES

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Experimental data obtained for film and mixed condensation of saturated air vapors (N_2, O_2, Ar) [1] is compared with the results of studies [11-13] of the condensation of pure saturated water vapors.

An analysis of the experimental data obtained by the author [1] in a study of the condensation of saturated air vapors (N_2, O_2, Ar) on the surface of a vertical brass tube (d = 22 / 16 mm, H = 0.94 m) showed that the coefficients of heat transfer for film condensation in the range of Reynolds numbers* from 694 to 1900 are located above and parallel to the theoretical Nusselt curve (Fig. 1).† The experimental data referring to drop condensation and, in part, to mixed condensation, were bunched around an empirical curve which is described by the equation

$$\frac{\bar{\alpha}}{\lambda}\left(\frac{\mu^2 g}{\gamma^2}\right)^{1/3} = 420\,\frac{3600\pi D\mu g}{4G}\,. \tag{1}$$

As is clear from Fig. 1, the experimental data for film condensation at p_k = 6 atm are located closer to the curve expressing the theoretical Nusselt equation but in the direction of increasing values of thermal flux (7165, 8190, 10,900, 12,400 W / m^2), as in the case of condensation at 4 atm (6500, 8800, 8900, 9500, 13,370 W / m^2).

The equation of the resultant curve has the form

$$\frac{\bar{\alpha}}{\lambda}\left(\frac{\mu^2 g}{\gamma^2}\right)^{1/3} = 2.2\left(\frac{4G}{3600\pi D\mu g}\right)^{-1/3}. \tag{2}$$

The dimensionless relations in Eq. (2) follow from the equation

$$\frac{\bar{\alpha}}{\lambda}\left(\frac{\mu^2 g}{\gamma^2}\right)^{1/3} = 1.468\,(\mathrm{Re})^{-1/3}, \tag{3}$$

obtained as the result of experimental [8] and theoretical [4] studies of fluid motion in a condensate film.

We point out that the increase of 50% in the correction coefficient of Eq. (2) in comparison with that of the Nusselt equation – 2.2 instead of 1.47 – resulted from visual observations of wave flow in the condensate film (N_2, O_2, Ar) and from its characteristic Reynolds numbers from 694 to 1900 calculated from the expression

$$x = \mathrm{Re} = \frac{4G}{3600\pi D\mu g}\,. \tag{4}$$

*The Reynolds number is related to the annular cross section of the flow channel of the condensing vapor.
†The dashed curve of Kirkbride [8] and Badger [14] plotted in Fig. 1 satisfies the conditions for turbulent flow of the film at Re > 2100 and is outside the limits of our experiments.

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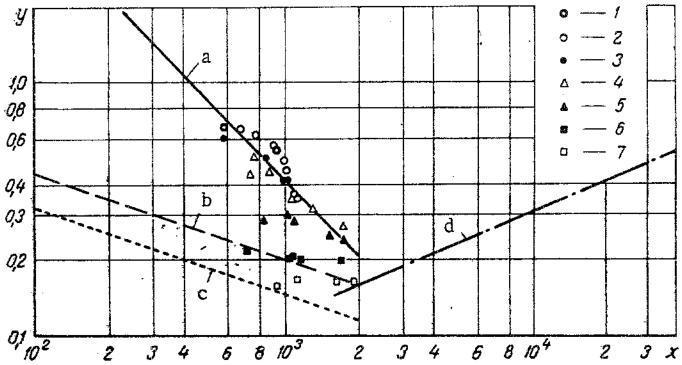

Fig. 1. Behavior of heat transfer during condensation of air vapors (N_2, O_2, Ar) in the coordinates of Kirkbride [8] and Gudymchuk – Konstantinov [4], $x = Re = 4G / 3600\pi D\mu g$, $y = (\bar{\alpha} / \lambda)(\mu^2 g / \gamma^2)^{1/3}$: a) experimental curve from Eq. (1); b) experimental curve from Eq. (2); c) theoretical Nusselt curve; d) from Kirkbride, $y = 0.0077\, x^{0.4}$; 1) p_K = 1.1 atm; 2) 1.25 atm; 3) 1.50 atm; 4) 2 atm (drop condensation); 5) 3 atm (mixed condensation); 6) 4 atm (film condensation).

This is in agreement with the work of Kapitsa [2] devoted to a theoretical analysis of wave motion in a fluid film on a vertical tube and with experimental studies [1, 3-13] on heat transfer during condensation of pure saturated water vapors on vertical tubes and, specifically, of the wave mode of film motion on a vertical wall [4-9].

Thus, according to [2], breakdown of the laminar nature of film flow arises during its transition into wave flow (Fig. 2) with the average film thickness being 7% less than that for the wave-free laminar mode and the average value of $1/\delta$ being 21% greater. Therefore, the value of $\bar{\alpha}$ for the wave mode of film flow is greater than that calculated by the Nusselt formula

$$\bar{\alpha} = 0.943 \left(\frac{r\gamma^2\lambda^3}{\mu (t_s - t_w) H} \right)^{1/4} \tag{5}$$

by the same amount, which this formula does not take into account. This is in agreement with the estimates of Kutateladze [5] and McAdams [7], according to which the experimental values of α are higher by 20%, on the average, than the theoretical values because of the unstable mode of fluid film motion on a vertical

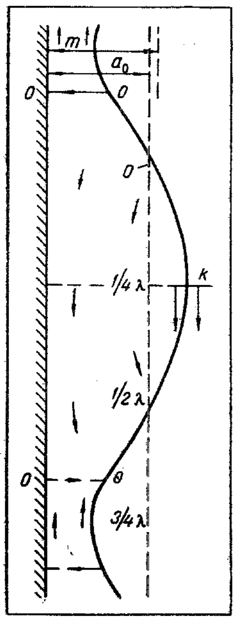

Fig. 2. Distribution of velocities for wave mode of fluid flow in a film according to the approximate theory of Kapitsa [2] [k) constant phase velocity; m) thickness of flow layer; a_0) average thickness of flow layer; λ) wavelength].

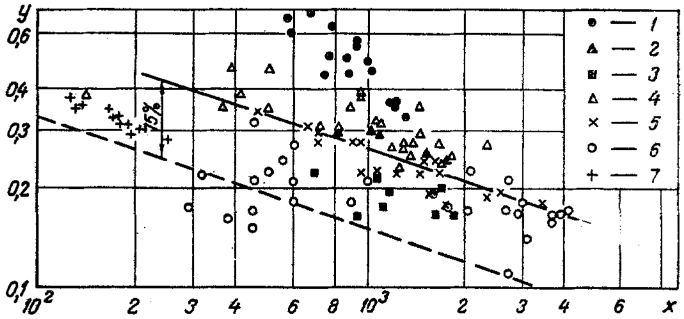

Fig. 3. Comparison of experimental data 1, 2, 3 [1] for condensation of air vapors (see Fig. 1 for notation) with experimental data from studies of the condensation of water vapors [4) Fragen, tube, H = 2.4 m; 5) [11], tube, H = 3.6 m; 6) [12], tube, H = 6 m; 7) [13], plate, H = 0.114 m].

wall. In fact, a mode is observed, as a rule, in which the film thickness varies periodically at each given point [2]. A condensate film on a vertical wall pulsates.

From data in [6], the extent of the wave-free zone of laminar flow for a condensate film of water vapor is characterized by a value Re $\leq$ 30, and wave flow develops in proportion to the increase in Re values to 2000-2500. The correction factor in the Nusselt formula, according to the data in [6], varies from 1 at Re = 30 to ~1.6 at Re = 2000-2500. For calculation of heat transfer during condensation of water vapor on vertical tubes, it is recommended [6] that the following relation be used for 30 < Re < 2000-2500:

$$\frac{\bar{\alpha}}{\lambda}\left(\frac{\mu^2 g}{\gamma^2}\right)^{1/3} = 1.05\mathrm{Re}^{-2/9}. \tag{6}$$

Friedman and Miller recommend [9] that the mode of film motion for Re from 25 to 1500 be called pseudolaminar.

The discussion above was the basis for the conclusion that the general Nusselt formula for laminar film flow at Re < 2000 was also valid for the calculation of the heat-transfer coefficient for the condensation of a mixture of saturated vapors (in the absence of noncondensing gases), the components of which are soluble to an unlimited extent in the condensate formed. In order to confirm the correctness of this conclusion, a comparison of the data for the condensation of mixtures of air vapors (N_2, O_2, Ar) with published results [11, 12] for the condensation of pure saturated water vapors on vertical tubes is presented in Fig. 3.

Plotted in Fig. 3 in the coordinates of the version of the analysis given above [8, 4] are 83 experimental points from the authors mentioned* on the condensation of water vapor, including 14 points for a vertical plate [13]. Also plotted are 32 points representing data obtained by the author [1] for the condensation of saturated air vapors (N_2, O_2, Ar). Of the points referring to film condensation, nine are located between the Nusselt curve (dashed curve) and the curve drawn parallel to it characterizing the spread of the 83 experimental points specified.

The experimental data relating to drop condensation lie higher in accordance with their heat-transfer coefficient values from 4600 to 8800 W/m$^2\cdot$deg.

Some dispersion of the experimental points which is observed in Figs. 1 and 3 may be caused to a known extent by the difficulties of measuring small temperature differences from 0.86 to 5.3°C in our experiments.

Figure 3 indicates that a calculation of the heat-transfer coefficient for Re < 2000 can be made from Eq. (2) with acceptable practical accuracy for film condensation on the surfaces of vertical tubes from a mixture of vapors in the absence of noncondensing gases.

*Comparison of experimental data on condensation of water vapor on vertical tubes and theoretical calculations for film condensation were taken from the monograph by McAdams (translated from the English), Metallurgizdat (1961), p. 454, Figs. 13 and 14.

NOTATION

$\bar{\alpha}$ is the heat-transfer coefficient, W/m^2·deg;
λ is the thermal conductivity, W/m·deg;
μ is the viscosity, N·sec/m^2;
γ is the specific weight, N/m^3;
r is the heat of evaporation, J/kg;
g is the acceleration of gravity, m/sec;
G is the mass flow rate of liquid, kg/h;
H is the height, m;
D is the diameter, m.

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