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# GENERALIZATION OF TEST RESULTS ON HEAT TRANSFER IN FILM BOILING UNDER NATURAL CONVECTION CONDITIONS

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Experimental results on heat transfer during film boiling in a large volume are compared for 13 fluids and with the computational dependences of different authors.

A large quantity of experimental results on the heat transfer during film boiling in a large volume have been obtained up to now. Empirical and theoretical dependences for the computation of the heat transfer are proposed in a number of papers [1-6]. We have compared these dependences with each other and with test results obtained during film boiling on vertical surfaces as well as on horizontal cylinders and spheres of diameter $D \gg l_{cr}$.

A theoretical analysis of film boiling permits one to establish the dimensionless parameters governing the process and to obtain the structural form of the criterial formula for the heat transfer in the form $Nu = f(Ra, K_v)$. The formulas of different authors, which we have reduced to this form, are represented in Table 1.

Characteristics of the working sections and the range of variation of the governing parameters for the experiments included in the generalization are presented in Table 2.

TABLE 1. Theoretical and Empirical Dependences on Heat Transfer during Film Boiling

| Author | Heating-surface geometry | Formula | |
|---|---|---|---|
| Labuntsov [1] | Vertical | $Nu = 0.25\,Ra^{1/3}$ | (1) |
| Borishanskii, Fokin [2] | Vertical | $Nu = \begin{cases} 0.28Ra^{1/3}Pr^{-1/3} & \text{for } \frac{\mu_l}{\mu_v}\frac{K_v}{Pr} < 63 \\ 0.0286Ra^{1/3}Pr^{-1/3}\left(\frac{\mu_l}{\mu_v}\frac{K_v}{Pr}\right)^{0.55} & \text{for } \frac{\mu_l}{\mu_v}\frac{K_v}{Pr} > 63 \end{cases}$ | (2) |
| Bulanova, Pron'ko [3] | Vertical and horizontal | $Nu = 0.134Ra^{1/3}\left(\frac{1}{K_v}\right)^{1/3}$ | (3) |
| Frederking, Clark [4] | Sphere ($D > l_{cr}$) | $Nu = 0.14Ra^{1/3}\left(0.5 + \frac{1}{K_v}\right)^{1/4}$ | (4) |
| Hendricks, Baumeister [5] | Sphere ($D > l_{cr}$) | $Nu = 0.35Ra^{1/4}\left(0.5 + \frac{1}{K_v}\right)^{1/4}$ | (5) |
| Breen, Westwater [6] | Horizontal cylinder ($D > l_{cr}$) | $Nu = 0.38Ra^{1/4}\frac{\sqrt{1 + 0.34K_v}}{K_v^{1/4}}$ | (6) |

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We superposed test results from [2, 3, 7-14] on a graph in the coordinates $\alpha = f(\Delta T)$. An average curve was determined for each working body at constant pressure by the method of least squares. The average curves obtained are represented in Fig. 1 in the coordinates $Nu = f(Ra)$. Superposed for comparison are the computational dependences (1)-(6), where Pr = 1 in (2) and $K_V = 1$ in (3)-(6).

It is seen from Fig. 1 that a formula of the form $Nu \sim Ra^{1/3}$ best describes the test results. This afforded the possibility of showing the influence of the dimensionless temperature head on the heat transfer.

Average test results from [2, 3, 7-14] and the computational dependences (1) and (4) are presented in Fig. 2 in the coordinates $Nu \sim Ra^{-1/3} = f(K_V)$.

It follows from Fig. 2 that the heat transfer is practically independent of the dimensionless temperature head $K_V$. All the test results are located between the Labuntsov formula (1) and the known formula for heat transfer for developed natural convection in a single-phase medium [15]:

$$Nu = 0.13\, Ra^{1/3}. \qquad (7)$$

The Frederking–Clark [4] expression (4) describes the experimental results well only in the range of small values of $K_V$.

The test results in the whole range of dimensionless temperature heads $K_V$ are generalized satisfactorily by the expression

$$Nu = 0.18\, Ra^{1/3}, \qquad (8)$$

TABLE 2. Experimental Investigations of Heat Transfer during Film Boiling

| Author | Working sections, mm | Working body | Pressure, $10^5$ N/m$^2$ | Temperature head, °K |
|---|---|---|---|---|
| Borishanskii, Fokin [2] | Vertical cylinders $H \le 80$, $D = 2.5$-$3.5$ | n-Hexane | 1 | 350 – 850 |
| | | Ethyl ether | 1 | 300 – 950 |
| | | Benzene | 1 – 10 | 350 – 1050 |
| | | Ethanol | 1 – 10 | 450 – 1000 |
| Hsu, Westwater [7] | Vertical cylinders H = 51-165 D = 9.5-19 | Methanol | 1 | 110 – 180 |
| | | Carbon tetrachloride | 1 | 100 – 160 |
| | | Nitrogen | 1 | 320 – 420 |
| | | Argon | 1 | 320 – 420 |
| Class et al. [8] | Vertical plate 25.4 × 559 | Hydrogen | 1 – 8.7 | 50 – 320 |
| Heath, Costello [11] | | Ethanol | 1 | 700 – 900 |
| Kalanin et al. [9] | Vertical cylinder H = 200, D = 10 | Nitrogen | 1 | 50 – 250 |
| | | Oxygen | 1 | 100 – 250 |
| | | Ethanol | 1 | 200 – 450 |
| | | Freon-12 | 1 | 100 – 150 |
| | | Freon-13 | 1 | 100 – 150 |
| Suryanaraiyana, Mert [10] | Vertical cylinder H = 178, D = 25.4 | Nitrogen | 1 | 50 – 170 |
| Bewilogua et al. [12] | Vertical cylinder H = 1.6D | Hydrogen | 1 | 50 – 250 |
| | | Oxygen | 1 | 50 – 250 |
| | | Nitrogen | 1 | 50 – 250 |
| | | Argon | 1 | 50 – 250 |
| | | Neon | 1 | 50 – 250 |
| Ruzicka [13] | Horizontal cylinder | Nitrogen | 1 | 50 – 200 |
| Bulanova, Pron'ko [3] | Vertical and horizontal cylinders | Nitrogen | 1 | 40 – 200 |
| Mert, Clark [14] | Sphere D = 25.4 | Nitrogen | 1 – 5 | 40 – 200 |

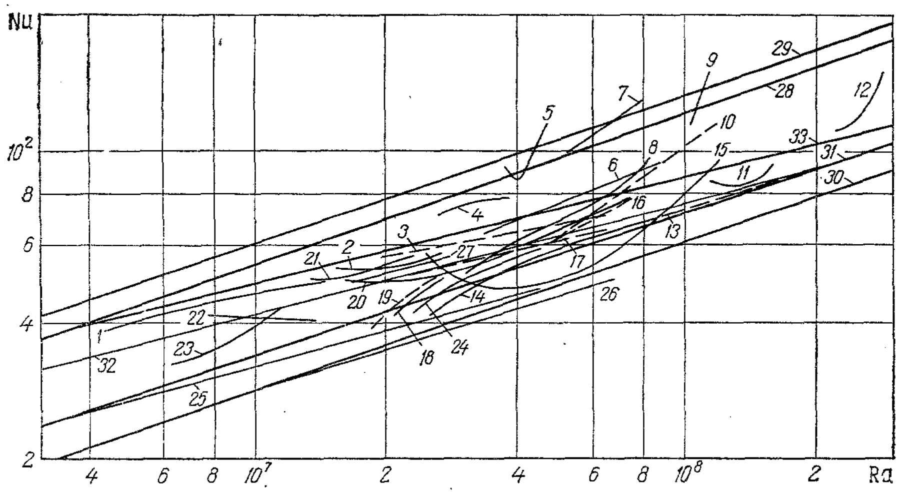


Fig. 1. Generalization of test results on heat transfer during film boiling: 1, 2, 4, 7) ethanol [2] (P = 1, 2.67, 5, and 10 atm, respectively); 3) n-hexane [2]; 5) methanol [7]; 6) hydrogen [8]; 8) oxygen [9]; 9) carbon tetrachloride [7]; 10) nitrogen [10]; 11, 12, 21) benzene [2] (P = 5, 10, and 1 atm); 13, 16, 17, 19) ethanol [11] ($g/g_0$ = 21.67, 7.36, 5.54, and 3.9, respectively); 14) nitrogen [9]; 15) nitrogen [12]; 18) ethanol [9]; 20) ethyl ether [2]; 22) argon [7]; 23) nitrogen [7]; 24) oxygen [12]; 25) neon [12]; 26) hydrogen [12]; 27) argon [12]; 28) formula (1); 29) (2); 30) (3); 31) (4); 32) (5); 33) (6).

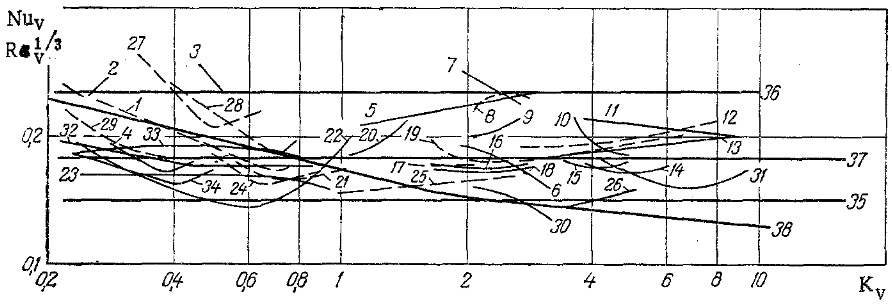


Fig. 2. Influence of the dimensionless temperature head on the heat transfer: 1) nitrogen [10]; 2) methanol [7]; 3) carbon tetrachloride [7]; 4) oxygen [9]; 5, 7, 8, 9) ethanol [2] (P = 1, 10, 5, and 2.67 atm, respectively); 6, 16, 17, 18) ethanol [11] ($g/g_0$ = 21, 3.9, 7.36, and 5.54); 10, 14, 15) benzene [2] (P = 10, 1, and 5 atm); 11) hydrogen [8]; 12) n-hexane [2]; 13) ethyl ether [2]; 19) nitrogen [7]; 20) argon [7]; 21) ethanol [9]; 22) nitrogen [13]; 23) nitrogen [9]; 24) oxygen [12]; 25) neon [12]; 26) hydrogen [12]; 27) argon [12]; 28) nitrogen [12]; 29) nitrogen [3]; 30) ethanol [11]; 31) hydrogen [8]; 32, 33, 34) nitrogen [14] (P = 1, 3, and 5 atm, respectively); 35) formula (7); 36) (1); 37) (8); 38) (4).

where the properties of the vapor are taken at the mean temperature $T_m = (T_s + T_w)/2$. The dependence (8) can be recommended for computing the heat transfer during film boiling of a saturated fluid in a large volume.

## NOTATION

$a$, thermal diffusivity; $c_p$, specific heat; D, heating-surface diameter; g, acceleration, g = 9.81 m/sec²; H, heating-surface height; $K_v = c_{p_v}\Delta T/r$, dimensionless temperature head; $l_0 = \sqrt{\sigma/[g(\rho_l - \rho_v)]}$, capillary constant; $l_{cr} = 2\pi l_0$, critical wavelength; $Nu = \alpha l_0/\lambda$, Nusselt criterion; p, pressure; $Pr = \nu/a$, Prandtl number; $Ra = (g l_0^3/\nu_v a_v)[(\rho_l - \rho_v)/\rho_v]$, modified Rayleigh number; T, temperature; α, heat-transfer coefficient; $\Delta T = T_w - T_s$, temperature head; λ, thermal conductivity; μ, dynamic viscosity; ν, kinematic viscosity; ρ, density; σ, surface tension. Indices: $l$, liquid; s, saturation; v, vapor; w, wall; m, mean.

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