NOTATION

V, unit volume of material; V_p, pore volume in material; V_d, dry pore volume; V_l, liquid volume; V_m, moist pore volume; V_s, skeleton volume; Π, porosity; ω, moisture content; b, parameter describing quantity of moist pores; λ_1, λ_g, λ_d, λ_m, thermal conductivities of solid skeleton, gas, diffusion component, and moist pore, W/(m·K); D, D', diffusion coefficients for vapor and air in smooth slot and porous material, m^2/sec; R, universal gas constant, J/(mole·K); T, absolute temperature, K; P, total pressure of gas mixture; P', partial pressure of liquid vapor, N/m^2; r, heat of vapor formation, kJ/kg; molecular mass, kg/mole; λ_{ij}, thermal conductivity of binary mixture of components i and j, W/(m·K); m_i, m_j, volume concentrations of components i and j; c_j, parameter dependent on volume concentration of component j.

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THE GENERALITY OF EQUATIONS FOR MIXED-CONVECTIVE HEAT TRANSFER TO LIQUIDS AT SUPERCRITICAL PRESSURE IN VERTICAL PIPES

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Using experimental data for helium at supercritical pressure which were obtained for ascending and descending flow in a vertical pipe, we verified the validity of a number of known equations for mixed-convective heat transfer.

Several equations are being recommended today for calculating mixed-convective heat transfer to liquids at supercritical pressure in vertical pipes; these equations are essentially based on experimental data obtained for water and carbon dioxide:

for descending flow [1]

$$\mathrm{Nu} = \mathrm{Nu_c} f(K), \tag{1}$$

where $\mathrm{Nu_c} = \mathrm{Nu_0} (\bar{c}_p/c_{p\ell})^n (\rho_w/\rho_\ell)^{0.3}$ [2]; $f(K) = 1$ for $K = (1 - \rho_w/\rho_\ell)\,\mathrm{Gr/Re^2} < 0.15$, $f(K) = 2.75 K^{0.46}$ for $0.15 < K < 6$,

for ascending and descending flow in the region $\mathrm{Gr/Re^2} < 0.6$ [3]

$$\mathrm{Nu_c} = \frac{\mathrm{Re\,Pr}\,\xi_1/8}{1 + 12.7\sqrt{\xi_1/8}\,\{[\mathrm{Pr}^*\rho_\ell/\rho_1(1+K)]^{0.66} - 1 - 0.1K^2\}}, \tag{2}$$

where ξ_1, Pr^*, ρ_1 and K are the parameters defined in [3],

for ascending flow [4]

$$\mathrm{Nu} = \mathrm{Nu_c} f(K), \tag{3}$$

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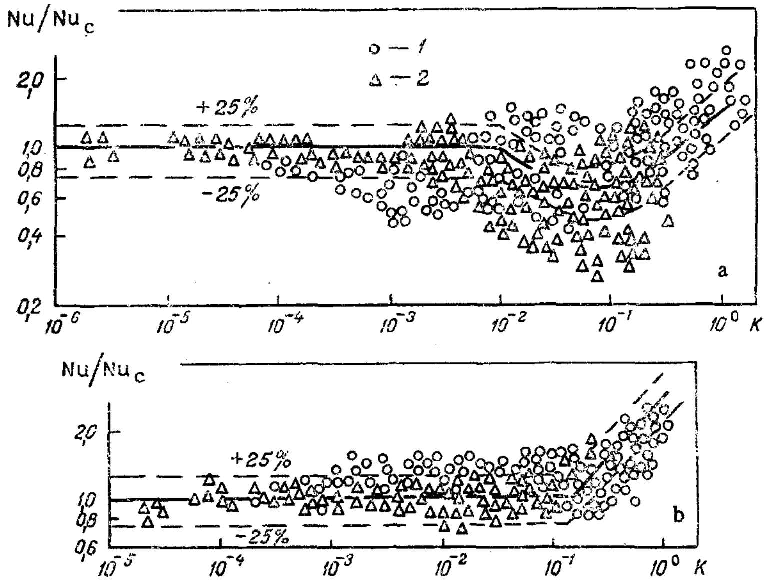

Fig. 1. Experimental data for helium in the coordinates of [1] and [3]: 1) $3 \cdot 10^3 < Re < 10^4$; 2) $Re > 10^4$. Solid curves: a) according to Eq. (3); b) according to (1). $K = (1-\rho_w/\rho_l)\,Gr/Re^2$.

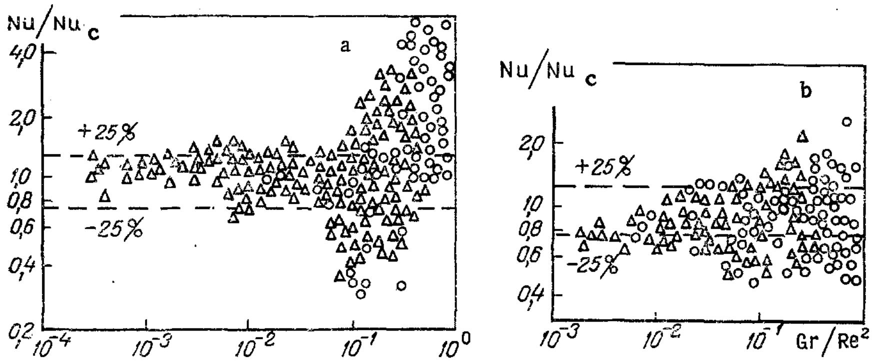

Fig. 2. Experimental data for helium in the coordinates of [2]. For the notation of the points, see Fig. 1.

where $Nu_c = Nu_0(\bar{c}_p/c_{pl})^n(\rho_c/\rho_l)^{0.4}$ [4]; $f(K) = 1$ for $K = 1\ (1-\rho_w/\rho_l)Gr/Re^2 < 0.01$; for values of K = 0.01; 0.02; 0.04; 0.06; 0.08; 0.1; 0.2; 0.4 f(K) is equal to 1; 0.88; 0.72; 0.67; 0.65; 0.65; 0.74; 1, respectively; $f(K) = 1.4K^{0.37}$ for $0.4 < K < 10$,

for ascending flow [5]

$$Nu = Nu_c f(K), \tag{4}$$

where $Nu_c = Nu_0[2/(\sqrt{0.8\psi + 0.2} + 1)]^2(\bar{c}_p/c_{pl})^{0.28}$ [6]; $f(K) = 1$ for $K = Ra_A/Re^2 < 4.5 \cdot 10^{-4}$; $f(K) = 6.1\,K^{0.235}$ for $4.5 \cdot 10^{-4} < K < 1$,

for descending flow [7]

$$Nu = Nu_c f(K), \tag{5}$$

where $Nu_c = Nu_0[2/(\sqrt{0.8\psi + 0.2} + 1)]^2(\bar{c}_p/c_{pl})^{0.28}$ [6]; $f(K) = 1$ for $K = Ra_A/Re^2 < 1.5 \cdot 10^{-4}$; $f(K) = (1 + 6750K)^{0.2}$ for $1.5 \cdot 10^{-4} < K < 1$.

It is not difficult to notice that almost all of the studies obtaining equations for mixed-convective heat transfer use an approach based on determining how the ratio of the measured Nusselt number to its value for purely forced convection of the liquid at supercritical pressure varies as a function of the parameter determined by thermogravitation.

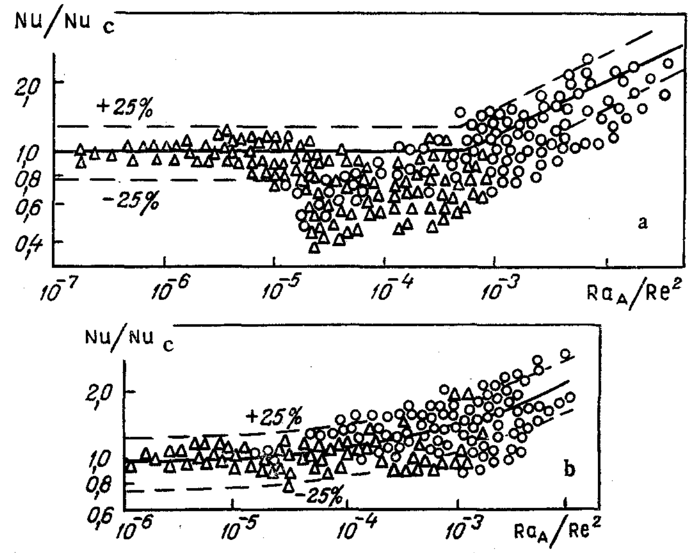

Fig. 3. Experimental data for helium in the coordinates of [4] and [5]. For the notation of the points, see Fig. 1. Solid curve: a) according to Eq. (4); b) according to (5).

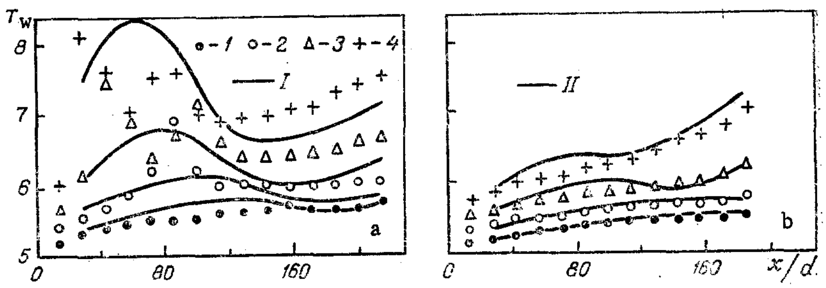

Fig. 4. Comparison of the experimental and calculated values of T_w for p = 0.25 MPa, $Re_{in} = 2 \cdot 10^4$ and different values of q for ascending flow (a) [1) q= 608 W/m²; 2) 799; 3) 1010; 4) 1250; I) according to to Eqs. (6) and (7)] and descending flow (b) [1) q= 575 W/m²; 2) 788; 3) 1020; 4) 1290; II) according to Eqs. (8) and (9)].

Various combinations of dimensionless numbers are chosen as the thermogravitation parameter. This fact alone is enough to indicate that Eqs. (1)-(5) cannot be regarded as general, since when they are used, it is possible to obtain widely differing values of the heat-transfer coefficient for the same regime parameters. The contradiction between the proposed equations is particularly noteworthy in the case of ascending flow. Thus, Eq. (3) predicts the existence of three regions of heat transfer, depending on the value of the thermogravitation parameter: in the first region the law of heat transfer for purely forced convection holds, in the second the thermogravitation causes a decrease in the ratio Nu/Nu_c (the so-called relative heat transfer) to values below unity, and in the third the relative heat transfer increases and becomes greater than unity. At the same time, the results of [5] did not indicate any region of decreasing heat transfer under the influence of thermogravitation. There was only an increase in the heat transfer over the value for purely forced convection. The results of that study also disagree with the experimental data on heat transfer to liquids with constant properties in [8].

In this situation, it is difficult to carry over the empirical equations for calculating the heat transfer from the case of one liquid to that of another and to a range of uninvestigated regime parameters without conducting additional investigations. However, what is urgently needed in practice is precisely some general relations which will be valid over wide intervals of variation of the flow rate, the thermal load, the pressure, the temperature, and the channel diameter. One of the methods for establishing the generality of these equations, which are based on the data for specific liquids in a certain region of thermogravitation parameters, is to verify them by comparing them with the results of experiments conducted on other liquids.

To verify the validity of the equations for mixed-convective heat transfer, we used the experimental data for helium at supercritical pressure in the transition region ($3 \cdot 10^3 < Re < 10^4$) and the turbulent region ($Re > 10^4$) of Reynolds numbers for ascending [9] and descending [10] flow. In Figs. 1-3 [a) asecnding flow; b) descending flow] the results of these experiments have been processed in the coordinates of [1-5].

In Fig. 1, Nu_c is the Nusselt number for heat transfer in the case of purely forced convection of a liquid at supercritical pressure. It can be seen that the dispersion of the experimental points reaches unacceptable values. Thus, the use of Eqs. (1) and (3) may lead to substantial errors.

In Fig. 2, Nu_c is the Nusselt number for heat transfer in the case of mixed convection. It can be seen that when $Gr/Re^2 < 0.05$, the difference between Nu and Nu_c for the bulk of the data does not exceed ± 25%. For higher values of Gr/Re^2 the difference increases sharply. The unsuitability of Eq. (2) for calculating the heat transfer to helium in the region $Gr/Re^2 > 0.05$ is obvious.

In Fig. 3, Nu_c is the Nusselt number for heat transfer in the case of purely forced convection of helium at supercritical pressure. It can be seen that calculation according to Eqs. (4) and (5) may also lead to errors. It was noted earlier that Eq. (4) for heat transfer in the case of ascending flow does not predict the regions in which the ratio Nu/Nu_c becomes less than 1 under the influence of thermogravitation. This fact contradicts, to a certain extent, the results of many investigations. At the same time, in [5] the generality of the equation obtained is based on experimental data for water, carbon dioxide, and helium taken from a large number of studies. Our verification showed that the proof of the generality of this equation failed to take account of a very important body of data for which $Nu/Nu_c < 1$.

The results obtained indicate that the equations given above for mixed convective heat transfer to liquids at supercritical pressure cover only special cases. For calculating heat transfer in ascending and descending flow in vertical pipes, we can propose the following equations, based on large amounts of experimental data for water, carbon dioxide, and helium in both the slightly and the strongly nonisothermal cases:

ascending flow [9]:

$$Nu = Nu_c(1 + 3.2 \cdot 10^8 K^{1,9})^{-1} \text{ for } K = Gr_A/Re^2 < 3 \cdot 10^{-5}, \tag{6}$$

$$Nu = Nu_c[6.85 K^{0,23} (1 + 4.84 \cdot 10^{-4} K^{-0,54})^{-1}] \text{ for } K > 3 \cdot 10^{-5}; \tag{7}$$

descending flow [10]:

$$Nu = Nu_c \text{ for } K < 10^{-5}, \tag{8}$$

$$Nu = Nu_c[0.45 (K \cdot 10^5)^{-0,33} + 0.55 (K \cdot 10^5)^{0,25}] \text{ for } K > 10^{-5}. \tag{9}$$

In determining Nu_c, we may use the equation for purely forced convection of a liquid at supercritical pressure from [10] or [11].

An example of the iterative calculation of T_w for several regimes of heat transfer to helium according to Eqs. (6), (7) and Eqs. (8), (9), with boundary coniditions of the second kind, is shown in Fig. 4. It can be seen that although the calculation of T_w yields acceptable quantitative agreement with the experimental values in the case of ascending and descending flows, the qualitative agreement between calculation and experiment in regimes with two maxima of T_w leaves something to be desired. An analysis of this case, which occurs only in ascending flow, will be a subsequent stage of the investigations.

NOTATION

T, temperature; p, pressure; q, specific heat flux; λ, heat-transfer coefficient; ρ, density; g, acceleration of free fall; d, diameter of the pipe; x, coordinate of the thermometric cross section; ν, kinematic coefficient of viscosity; c_p, specific heat at constant pressure; $\bar{c}_p = (h_w - h_l)/(T_w - T_l)$, average specific heat; h, enthalpy; β, coefficient of volumentric expansion; $\psi = 1 + \beta(T_w - T_l)$, parameter of nonisothermality; Nu, Re, Pr, Nusselt, Reynolds, Prandtl numbers; $Gr = g(1 - \rho_w/\rho_l)d^3/\nu^2$, $Gr_A = g\beta q d^4/4\lambda\nu^2 RePr$, Grashof numbers; $Ra_A = Gr_A Pr$, Rayleigh number. Subscripts: w, wall, l, liquid; 0, constant properties; c, calculated; in, inlet. Remark: the properties of dimensionless numbers are taken for the mass-average temperature of the liquid.

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