MODES OF "NORMAL" AND "DETERIORATED" HEAT EXCHANGE IN THE SINGLE-PHASE NEAR-CRITICAL REGION IN THE TURBULENT FLOW OF HELIUM IN TUBES

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The results of a study of heat transfer to helium in the single-phase near-critical region are presented. The boundaries of existence of the modes of "normal" and "deteriorated" heat exchange are established. A calculating dependence for the local heat exchange is proposed.

The creation of efficient cooling systems in the thermostatic control of different kinds of objects of cryogenic, electronic, electrical engineering, and other devices requires the comprehensive study of the processes of heat exchange in the turbulent flow of helium in the single-phase near-critical (supercritical) state.

As our studies [1-3] and the studies of other authors on helium [4-6] showed, in the single-phase near-critical region the local heat transfer can depend on the pressure, mass velocity, and heat-flux density, and it differs considerably from heat transfer to a stream with constant properties. However, these data are still insufficient for the determination of the main relationships of the heat-exchange processes which occur in the turbulent flow of helium, especially under the conditions of the mode of "deteriorated" heat exchange ($T_s \leqslant T_m \leqslant T_w$). Therefore, a further study was made of heat exchange during the turbulent flow of helium in the single-phase near-critical region, the results of which are presented in the present article.

The study was performed on nickel tubes of d = 1.04 mm (1.14 mm o.d. by 0.5 mm) and d = 0.7 mm (0.8 mm o.d. by 0.05 mm) in the pressure interval of $(3-20)\cdot 10^5$ N/m^2 and the temperature interval of 4.5-10°K under conditions of ascending, stabilized, turbulent flow of the liquid with variations in the mass velocity and heat-flux density within the following limits: ρw = 42-180 kg/m$^2\cdot$sec and Re = $(16-57)\cdot 10^3$, $q_w = (0.18-0.52)\cdot 10^4$ W/m^2.

The experimental installation, the test section, and the method of treatment of the data obtained are described in [1, 2].

The most characteristic results of the treatment of the test data in the form $\alpha_f = f(T_s)$ for pressures of 3, 4, 8, and $10\cdot 10^5$ N/m^2 are presented in Fig. 1.

It is seen from the figure that for each pressure in the interval of $(3-8)\cdot 10^5$ N/m^2 and a constant mass velocity the heat-exchange coefficient varies especially strongly in the region close to the pseudocritical temperature T_m. With a small heat-flux density in the range of values of $q_w = (0.18-0.30)\cdot 10^4$ W/m^2 (curve 1), when the mode of heat exchange is "normal" (T_s and $T_w \gtrapprox T_m$), the heat-exchange coefficient increases as the pseudocritical temperature is approached.

As the heat-flux density grows (curves 2, 3, and 4) within the range of values of q_w = $(0.37-0.52)\cdot 10^4$ W/m^2, when the mode of heat transfer corresponds to the conditions of the "deteriorated" mode ($T_s \leqslant T_m \leqslant T_w$), the heat-transfer intensity decreases markedly, especially in the region of pseudocritical temperatures. As seen from the figure, curves 2, 3, and 4 [for P = $(3-8)\cdot 10^5$ N/m^2] differ from curve 1, which indicates the large qualitative and quan-

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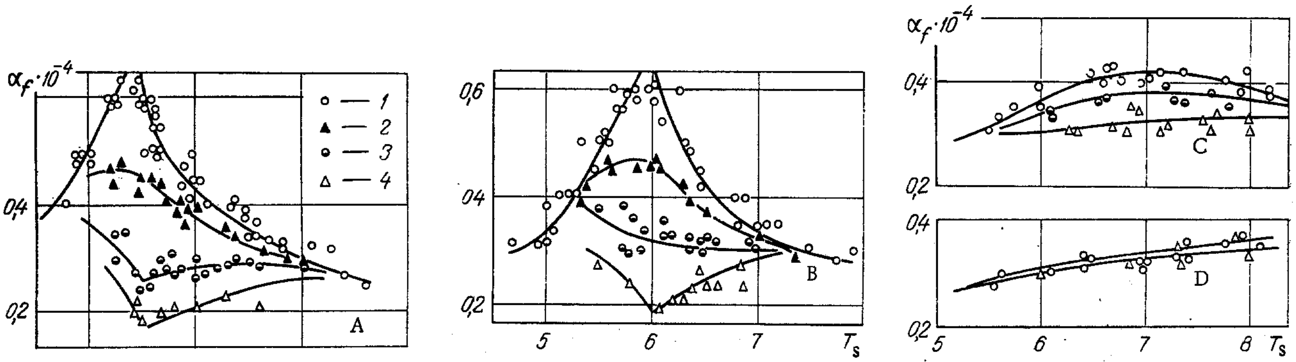

Fig. 1. Dependence of heat-exchange coefficient α_f ($W/m^2 \cdot {}^\circ K$) on the temperature T_s (°K) of the core of the stream at different pressures under the conditions of "normal" and "deteriorated" modes: A) $\rho\bar{w}$ = 93 $kg/m^2 \cdot sec$, P = $3 \cdot 10^5$ N/m^2; B) 98 and $4 \cdot 10^5$, respectively; C) 120 and $8 \cdot 10^5$; D) 100 and $10 \cdot 10^5$; 1) q_w = 0.30; 2) 0.37; 3) 0.45; 4) $0.52 \cdot 10^4$ W/m^2, d = 1.04 mm.

titative differences between the modes, evidently caused by the different nature of the heat transfer in the near-wall region.

However, these differences degenerate with an increase in pressure, and they vanish completely at a pressure of $10 \cdot 10^5$ N/m^2, which is connected with the character of the variation in thermophysical properties with temperature and pressure in the single-phase near-critical region.

A few relationships for the supercritical region exist in the literature. Of these the best known are the functions obtained in experiments with carbon dioxide and water [9, 10].

It was pointed out in [1] that the comparison made between these relationships and data which we obtained for helium corresponding to the conditions of the "normal" mode (T_s and $T_w \gtrless T_m$) revealed marked disagreements, especially under the conditions of T_s and $T_w \approx T_m$. However, the analysis of the data did not cover a wide range of mode parameters and was not conducted for the modes with "deteriorated" heat transfer. Meanwhile, with the obtaining of a sufficient quantity of experimental data such a comparison has become necessary.

In Fig. 2 in the form $Nu_{ex}/Nu_c = f(T_s/T_m)$, our data and the data from [4, 5, 6] are compared with the dependence for the supercritical region obtained from the experimental data for carbon dioxide and water in small-diameter stainless steel tubes under the conditions of turbulent flow of the liquid with variable thermophysical properties [9]:

$$Nu_c = Nu_{oc}(\rho_w/\rho_l)^{0.3}(\bar{c}_p/c_{ps})^n, \tag{1}$$

where $\bar{c}_p = (i_w - i_l)/(t_w - t_l)$; n = 0.4-0.7 is the exponent, which depends on the values T_w/T_m and T_s/T_m; Nu_{oc} is the Nusselt number, determined from the dependence for the constant properties [8].

As seen from the figure, satisfactory agreement with ± 25% accuracy both of our data and of the data of other authors (Nu_{ex}) with the calculated values Nu_c is observed primarily in regions relatively distant from the pseudocritical temperature ($T_s/T_m < 0.88$ and $T_s/T_m > 1.15$). This confirms the reliability of the results obtained by us and the correctness of the treatment of the data. At the same time this indicates a certain generality of the processes of heat transfer with the conditions in application to which Eq. (1) was obtained.

In the region close to the pseudocritical temperature ($0.88 \leqslant T_s/T_m \leqslant 1.15$), as seen from the figure, such agreement is not observed: the values of Nu_{ex} for experiments obtained under conditions of "normal" and "deteriorated" modes are predominately located above the calculated values Nu_c with considerable scatter of the experimental points.

The scatter of the points is also observed for the data of [5], obtained on a stainless steel tube (the remaining data do not cover this region), which is less, however, than for our values obtained on nickel tubes.

Somewhat better agreement is obtained with the dependence for water [10]:

$$Nu = 0.023 Re^{0.8} Pr_{min}^{0.8}, \tag{2}$$

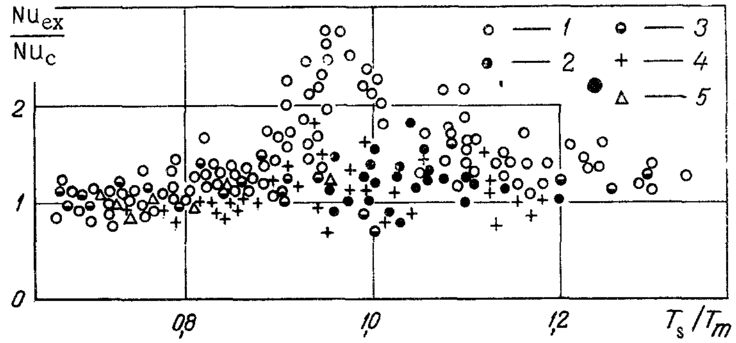

Fig. 2. Comparison of experimental data with dependence (1) for carbon dioxide: 1) $(3\text{-}20)\cdot10^5$ N/m^2 ("normal" mode of exchange); 2) $(3\text{-}8)\cdot10^5$ N/m^2 ("deteriorated" mode of heat exchange); 3) data from [4]; 4) from [5]; 5) from [6].

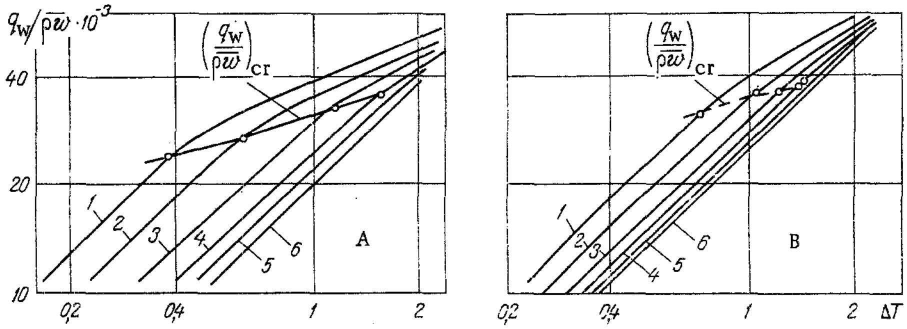

Fig. 3. Parameter $q_w/\overline{\rho w}$ (kJ/kg) as a function of temperature head ΔT (°K): A) $T_s/T_m = 0.96$; B) $T_s/T_m = 0.90$; 1) $3\cdot10^5$; 2) $4\cdot10^5$; 3) $6\cdot10^5$; 4) $8\cdot10^5$; 5) $10\cdot10^5$; 6) $15\cdot10^5$ N/m^2, $d = 1.04$ mm.

although on the whole the character of the deviations is about the same as in the comparison with (1).

Evidently, the observed deviations in the scatter of the experimental data from the data calculated from Eqs. (1) and (2) are due to the empirical nature of these functions, which in application to helium do not take into account the peculiarities of the heat-transfer processes in the immediate vicinity of the pseudocritical temperature. An understanding of their causes, however, requires the setting up of a detailed physical study of the hydrodynamic structure of the stream in this region which is extremely complex experimentally.

Certain experimental results for water and carbon dioxide are presented in [7, 11, 12] where the effect of the parameter $q_w/\overline{\rho w}$ on the heat-exchange intensity is shown. Moreover, it is shown in [11] that the parameter $q_w/\overline{\rho w}$ for these liquids can be basic to the determination of the boundaries of deterioration of heat transfer. In this connection our data were treated in the form $q_w/\overline{\rho w} = f(\Delta T)$ in the interval of $T_s/T_m = 0.75\text{-}1.35$ and pressures of $(3\text{-}8)\cdot10^5$ N/m^2.

In Fig. 3 the data are represented in these same coordinates for two stream cross sections.

It is seen from the figure that each pressure corresponds to its own curve, with curves 1-4[$(3\text{-}8)\cdot10^5$ N/m^2] considerably changing their curvature at certain "critical" values of the parameter $(q_w/\overline{\rho w})_{cr}$. This corresponds to the transition from the "normal" to the "deteriorated" mode of heat exchange. But the quantity $(q_w/\overline{\rho w})_{cr}$ decreases as the pressure grows. At the same time, curves 5 and 6 (10 and $15\cdot10^5$ N/m^2) do not undergo such changes: the "deteriorated" mode is not observed in this case. It is also seen that the spacing of the curves decreases with greater distance from the section with the reduced temperature $T_s/T_m = 1$ of the stream core (i.e., from the pseudocritical temperature). It is characteristic that under the conditions of the "deteriorated" mode curves 1-5 draw together with an increase in the parameter $q_w/\overline{\rho w}$, while the form of curves 1-4 approaches ever more to that of 5 and 6, not undergoing changes in their curvature in the entire range of values of $q_w/\overline{\rho w}$ and characterizing a mode of heat exchange which is close to convective with constant properties.

Thus, the boundaries of the modes with deteriorated heat transfer in the pressure range of $(3\text{-}8)\cdot 10^5$ N/m² (P/P_{cr} = 1.35-3.54) are determined, as follows from Fig. 3, by the following condition:

$$(q_w/\overline{\rho w})_{P/P_{cr},\,T_s/T_m} \geqslant [(q_w/\overline{\rho w})_{cr}]_{P/P_{cr},\,T_s/T_m} \tag{3}$$

or

$$\left[\frac{q_w/\overline{\rho w}}{(q_w/\overline{\rho w})_{cr}}\right]_{P/P_{cr},\,T_s/T_m} \geqslant 1. \tag{4}$$

On the basis of the expression (4) one can arrive at the ratio of dimensionless complexes in the form

$$\left[\frac{q_w/\overline{\rho w}\cdot i_s}{(q_w/\overline{\rho w}\cdot i_s)_{cr}}\right]_{P/P_{cr},\,T_s/T_m} = \left[\frac{h^+}{h^+_{cr}}\right]_{P/P_{cr},\,T_s/T_m} \geqslant 1, \tag{5}$$

where

$$i_s = i'_s - i_0 = \int_{T_0}^{T'_s} c_p dT.$$

The expression (5), first of all, allows one to estimate qualitatively the nature of the process: the "normal" or "deteriorated" mode of heat exchange occurs with the given mode parameters. However, considering the complexity of the determination of the complex $(q_w/\overline{\rho w}\cdot i_s)_{cr} = h^+_{cr}$ in real heat-exchange devices and systems, the following empirical equation is obtained for engineering calculations:

$$h^+_{cr} = h^+_{cr_0}\left(\frac{P}{P_{cr}}\right)^{-0.3}\left(\frac{T_s}{T_m}\right)^{-n}. \tag{6}$$

By the method of graphic analysis of the experimental data with an accuracy of ± 20% in the coordinates of $h^+_{cr}\cdot(T_s/T_m)^n$ and P/P_{cr} for values of P/P_{cr} = 1.33-3.54 and n = −0.9 with T_s/T_m = 1.0-1.35 and n = −3.5 with T_s/T_m = 0.75-1.00 it was found that $h^+_{cr_0} = 15\cdot 10^{-4}$. Then

$$h^+_{cr} = 15\cdot 10^{-4}\left(\frac{P}{P_{cr}}\right)^{-0.3}\left(\frac{T_s}{T_m}\right)^{-n}. \tag{7}$$

If one assumes that

$$h^+_{cr} = \frac{q_w}{\overline{\rho w}\, i_s} \approx \frac{q_w \beta}{\overline{\rho w}\, c_{p_s}},$$

then between the dimensionless number h^+_{cr}, characterizing the start of deterioration, and the deterioration criterion $\bar{q}$, obtained by the analysis of data for water and carbon dioxide [13] with the parameters T_s/T_m and P/P_{cr} being compared, a relationship can be established in the form

$$h^+_{cr} \simeq \bar{q}\sqrt{\xi/8}, \tag{8}$$

where

$$\bar{q} = \left(\frac{\beta_\rho}{c_p}\right)_{t_m}\left(\frac{q_w}{\overline{\rho w}}\right)\sqrt{\frac{8}{\xi}}, \tag{9}$$

which allows one indirectly to compare the results of the study on helium, on the one hand, and on water and carbon dioxide, on the other.

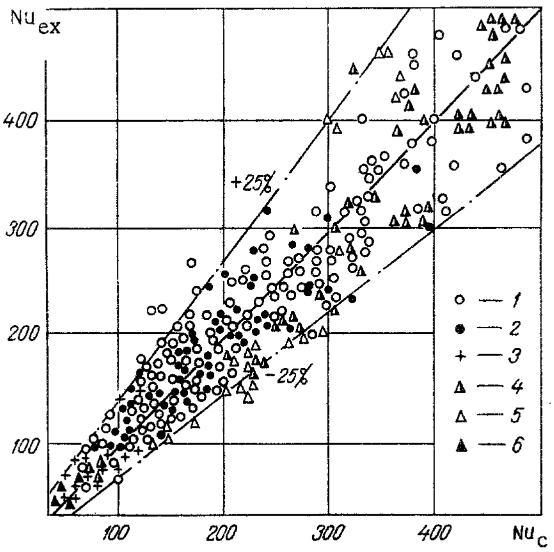

Fig. 4. Comparison of experimental data with those calculated by dependence (11): 1) $(3\text{–}8)\cdot 10^5$ N/m² ("normal" mode); 2) $(3\text{–}8)\cdot 10^5$ N/m² ("deteriorated" mode); 3) $(10\text{–}20)\cdot 10^5$ N/m²; 4) data from [4]; 5) from [5]; 6) from [6].

By solving the system of equations (7) and (8) for $\bar{q}$ with $T_s/T_m = 1$ and $P/P_{cr} = 1.33\text{–}1.55$ (the mean value $P/P_{cr} = 1.44$ was taken in the calculation, since the effect of the pressure was not allowed for in [13]) it was found that for helium $\bar{q} = 2.6\cdot 10^{-2}$. The disagreement with the value $\bar{q} = 3.4\cdot 10^{-2}$ for water and carbon dioxide obtained in [13] is 30%. This disagreement is comparatively small, which indicates the qualitative similarity of the heat-transfer mechanisms for helium and water occurring in the transition from the "normal" to the "deteriorated" mode of heat exchange.

By assuming that $h^+/h^+_{cr} = H$, one can arrive at a quantitative relationship in the form

$$H = 667\,\frac{q_w}{\overline{\rho w}\, i_s}\left(\frac{P}{P_{cr}}\right)^{0.3}\left(\frac{T_s}{T_m}\right)^{n} \geqslant 1, \tag{10}$$

where $n = 3.5$ with $T_s/T_m = 0.75\text{–}1.00$ and $n = 0.9$ with $T_s/T_m = 1.00\text{–}1.35$ in the interval of $P/P_{cr} = 1.33\text{–}3.54$.

The dimensionless number H allows one to make qualitative and quantitative estimates of the heat-exchange processes in the single-phase near-critical region under conditions of the ascending, stabilized, turbulent flow of helium in tubes.

On the basis of the experimental data a dependence for the local heat transfer is obtained which basically agrees structurally with that obtained in [1]:

$$\mathrm{Nu}_s = 0.033\,\mathrm{Re}_s^{0.8}\,\mathrm{Pr}_s\left(\frac{T_s}{T_m}\right)^{-0.5} F, \tag{11}$$

where $F = 1$ if $H \leqslant 1$ (the "normal" mode of heat exchange); $F = H^{-1.4}$ $(F < 1)$ if $H > 1$ (the "deteriorated" mode of heat exchange), with $P/P_{cr} = 1.33\text{–}3.54$ and $T_s/T_m = 0.75\text{–}1.35$; $F = 1$ with $P/P_{cr} = 3.54\text{–}8.84$, $T_s/T_m = 0.75\text{–}1.45$.

As is seen, in this dependence, in contrast to the majority of those known in the literature, the parameters determined from the wall temperature are eliminated, which considerably facilitates the performance of engineering calculations with boundary conditions of the second kind.

The dependence (11) generalizes the experimental data with an accuracy of ± 25% in the pressure range of $(3\text{–}20)\cdot 10^5$ N/m² and temperature range of 4.5–10°K (Fig. 4) obtained on nickel tubes of d = 0.7 and 1.04 mm with a turbulent ascending mode of flow (Re = 16,000–57,000).

The data of other investigators [4, 5, 6] are also generalized with the help of Eq. (11) (Fig. 4). Thus, the data from [4, 6] are generalized by this dependence within the limits of of ±25% (Fig. 4), while the experimental points obtained from the data of [5] are located below the calculated curve by an average of 20-30%.

NOTATION

d, tube diameter, mm; c_p, specific isobaric heat capacity, J/mole·°K; P, pressure, N/m²; q_w, heat-flux density at wall, W/m²; T, temperature, °K; ΔT, local temperature head, °K; T_m, pseudocritical temperature, °K; i, enthalpy, J/mole; α_f, local heat-transfer coefficient, W/m²·°K; $\overline{\rho w}$, mass velocity, kg/m²·sec; T_s/T_m, reduced temperature of stream core; β, coefficient of volumetric expansion, $°K^{-1}$; F, correction factor; H', h^+, dimensionless numbers. Indices: w, parameters of wall; s, parameters of stream core; 0, initial conditions; cr, critical

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HEAT TRANSFER BETWEEN ROTATING DISKS IN A CLOSED CAVITY

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The heat transfer of a disk in a closed rotating cavity with laminar and turbulent boundary layers is determined experimentally.

Information on heat transfer in closed rotating cavities is required when estimating the temperature state of the rotors of gas and steam turbines, electrical machinery, etc. The theoretical solution of this problem for the self-similar case of laminar convection has been examined in [1] and for the case when the laminar or turbulent boundary layers at the surfaces of the disks are separated by the core of the stream — in [2, 3].

The theoretical solutions are obtained with the use of a number of simplifying premises. Moreover, mass forces alter the boundaries of the modes of flow [4] and a theoretical analy-

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