HEAT TRANSFER IN THE FLOW OF SUPERCRITICAL-PRESSURE HELIUM WITH HIGH THERMAL LOADS

M. A. Valyuzhinich, V. M. Eroshenko,
and E. V. Kuznetsov

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A dependence is proposed taking account of the influence exerted on heat transfer by the change in thermophysical properties in the region of pseudocritical flow temperature and the effects of the initial section in strongly nonisothermal conditions.

Determining the heat transfer to helium in conditions of high thermal load (up to 10^5 W/m^2) entails calculating the cooling of various cryoenergetic systems in which intensive pulsed thermal perturbations are possible.

Recently, there have appeared numerous works in which the results of experimental investigation with a high rate of heating of helium in pulsed conditions are presented [1, 2]. In [3, 4], a nonsteady process consisting of several stages was considered: in the first stage, at small Fo, heat transfer occurs basically on account of nonsteady heat conduction; in the second, the influence of convective heat transfer is presominant.

In the second stage, the process may be conventionally regarded as quasisteady, and dependences obtained for steady conditions may be used to calculate the heat transfer.

In the case of variable fluid properties, which is especially important close to the critical point, the correctness of this approach and the accuracy of the dependences themselves for calculating heat transfer when extrapolated to regions of significant thermal load, as in the experiments of [8-10] for example, are questions of particular importance. It is obvious that such calculations require experimental verification.

The results of experimental investigations of the heat transfer to helium at supercritical pressure in conditions of steady intensive thermal loads are given below, together with a comparison with known results on heat transfer to helium in pulsed heating conditions.

Experiments were conducted in the following parameter ranges: $P = (0.24\text{-}0.68)\cdot 10^6$ N/m^2 ($P/P_{cr} = 1.05\text{-}3.1$); $G = (0.037\text{-}0.200)\cdot 10^{-3}$ kg/sec ($Re = 8\cdot 10^3\text{-}6.5\cdot 10^4$); $q_w = 900\text{-}6000$ W/m^2; $T_{in} = 4.41\text{-}7.1$ K; $T/T_m = 0.8\text{-}6$; $A = q_w d^{0.2}/(\rho u)^{0.8} = 10\text{-}100$ SI units.

The experimental model was a horizontal stainless-steel tube with an internal diameter d = 1.4 mm; the length of the heated section L = 545 mm, and the length of the preliminary hydrodynamic-stabilization section was 50d. The wall temperature was monitored over the mean generatrix of the tube at distances x/d = 11, 18, 25, 32, 40, 50, 61, 75, 93, 114, 140, 182, and 239 from the beginning of the heated section. A diagram of the apparatus was given in [5].

With the aim of determining the heat-transfer coefficient more accurately without taking account of the influence of free convection on the heat transfer, the sensors were established on the mean generatrix of the horizontal tube [6].

It is known that increase in thermal load leads to the appearance of low-frequency pulsations in the pressure and flow rate and temperature oscillations of the wall. To reach the experimental goals, stabilization of the flow in the working section is of particular importance. To this end, a bimetallic tube [7] made from stainless steel and copper (diameter 2 mm) was used as the pulsed tube in measuring the pressure. At the channel inlet, preceding the hydrodynamic-stabilization section, a disk with a cross section of 0.6 mm was established.

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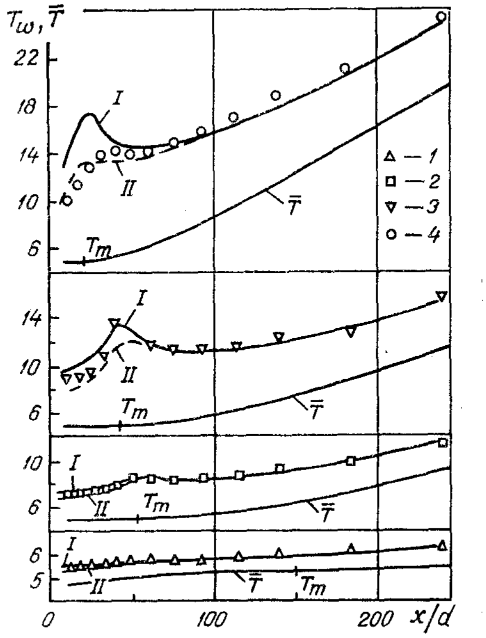

Fig. 1. Variation in wall temperature with increase in heating intensity (P = 0.25 MPa): 1) A = 11 SI units; 2) 26; 3) 40; 4) 56; I) calculation by Eq. (1); II) by Eq. (2). $\bar{T}$, °K.

As a result of the experiments, two characteristic regions within which the heat transfer is significantly different in character have been distinguished: the region of quasistabilized heat transfer and the region which may be called the initial thermal section. The length of the initial section was not fixed, and depended on the flow parameters, the boundary conditions, and the helium flow rate.

In the region of quasistabilized heat transfer, the well-known laws obtained on heating turbulent liquid flows in the near-critical state are observed. With increase in thermal load, the heat transfer first increases and then monotonically decreases, especially strongly when $\bar{T} = T_m$. Nonmonotonic increase in wall temperature over the length of the channel is noted here, with peaks of T_w coinciding with the position of the cross section with a mean-mass flow temperature of T_m (Fig. 1). Experimental results in this region are satisfactorily generalized by Eq. (1) from [7]:

$$\frac{\mathrm{Nu_{st}}}{\mathrm{Nu_0}} = \frac{(T_w/\bar{T})^{-0.5}}{m+(1-m)\dfrac{c_p(T_w-\bar{T})}{H_w-\bar{H}}+0.4\exp\left(1-\dfrac{T_w}{T^*}\right)\beta(T_w-\bar{T})\,\mathrm{Pr}^{-0.6}(T_w/\bar{T})^{-0.5}}, \qquad (1)$$

where m = 0.6.

Comparison of the present experimental results and the results of [8-10] shows satisfactory agreement when the cross section with a helium temperature $\bar{T} = T_m$ is sufficiently remote from the channel inlet (x/d > 50). Equation (1), generalizing a large mass of experimental data on heat transfer to supercritical-pressure helium on the section of quasistabilized heat transfer, may serve as the basic equation for estimating the heat transfer in the initial section.

Analysis shows that Eq. (1) does not satisfactorily generalize the heat transfer over the whole length of the channel. It is evident from Fig. 1 that the greatest deviation of the experimental and theoretical data is observed on the section adjacent to the channel inlet. The heat transfer in the initial section increases significantly if the cross section with the mean-mass flow temperature of T_m is in the section where x/d < 50.

Comparison of experimental data on heat transfer for different helium temperatures at the inlet to the working section, other conditions being equal (and, especially important, with equal flow enthalpies), shows that the length of the section within which the heat transfer depends on the temperature at the inlet is variable but does not exceed x_{max} = 50d from the channel inlet and depends on the position of the cross section with $\bar{T} = T_m$ relative to the inlet. Thus, deviation of the heat-transfer coefficients in the initial section of the tube from theoretical values for quasistabilized heat transfer (Fig. 2) may be explained by the influence of thermal stabilization of the flow, which is delayed if the greatest change in the thermophysical properties and flow parameters occurs in the initial section.

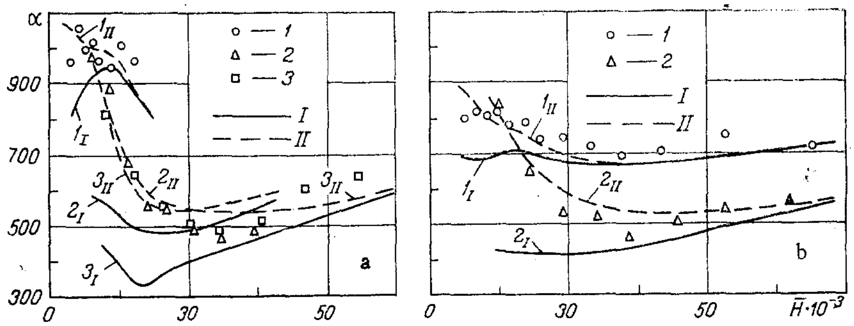

Fig. 2. Variation in heat-transfer coefficient with increase in heating intensity: a) P = 0.3 MPa; $\overline{\rho u}$ = 42 kgf/m²·sec: 1) A = 20 SI units; 2) 52; 3) 81. b) P = 0.6 MPa, $\overline{\rho u}$ = 37 kgf/m²·sec: 1) A = 30 SI units; 2) 89. I) Calculation by Eq. (1); II) by Eq. (2). α, W/m²·K; $\bar{H}$, J/kg.

The experimental data obtained, including the initial section, may be generalized by the following dependence on the basis of Eq. (1):

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0}=\varepsilon_l\frac{(T_w/\bar{T})^{-n}}{m+(1-m)\dfrac{c_p(T_w-\bar{T})}{H_w-\bar{H}}+0.4\exp\left(1-\dfrac{T_w}{T^*}\right)\beta(T_w-\bar{T})\,\mathrm{Pr}^{-0.6}(T_w/\bar{T})^{-n}}, \tag{2}$$

where $n = 0.5 - [1 - 0.8(d/x)^{0.8}]/\exp(0.04x/d)$; $\varepsilon_l = 0.86 + 0.54(d/x)^{0.4}$ is a correction taking account of the change in heat transfer in the initial section in quasiisothermal conditions [12].

Equations (1) and (2) generalize the experimental data within the range A = 1-100 SI units ($q_{\max} = 10^4$ W/m²). In a wider range of A, experiments with supercritical-pressure helium were conducted only in [2]: $q_w = (0.1\text{-}10)\cdot 10^4$ W/m²; A = 3-820 SI units. Heat transfer with a pulsed thermal load in conditions of induced convection was considered. An interesting feature of these experiments was the determination of the heat-transfer coefficients at the stage of nonsteady heat transfer and at the stage of stabilized convective heat transfer. In these experiments, increase in heat transfer was noted with increase in thermal load, in contrast to the results of [8-10], in which reduction in heat transfer with increase in q_w was noted – "deteriorated" heat-transfer conditions.

Taking into account that in the experiments of [2] the wall temperature was measured at a distance x/d_{equ} = 2.3-3.3 from the inlet to the heated section, this result may be explained by the significant influence of the initial section on the heat transfer (Fig. 2). In Fig. 3, the experimental results at the stage of convective heat transfer [2] and calculations by the dependence of [11] for quasistabilized heat transfer and Eq. (2), taking account of the influence of the initial section, are shown. It is evident from Fig. 3a that, disregarding the influence of the initial section on the heat transfer in strongly nonisothermal conditions leads to significant (up to 700%) disagreement of the experimental and theoretical results. This difference cannot be taken into account by introducing corrections in the initial section for liquids with constant properties (of type ε_l), which increase the heat transfer by no more than 30% at the given x/d_{equ}. The agreement of the heat transfer (Fig. 3b) and wall temperature (Fig. 4) is more satisfactory.

Comparison of the theoretical and experimental data leads to the conclusion that Eq. (2) overall correctly reflects the above-noted features in the variation of the heat-transfer coefficient as a function of the thermal load. This dependence is formally related to the decrease in magnitude and change in sign of n for the temperature factor with decrease in distance from the inlet and reflects the influence of the heat flux on the increase in turbulent transfer in the boundary layer in the initial section of the tube, in contrast to the section of quasistabilized heat transfer, where intensification in nonisothermal conditions leads to deturbulization of the flux and reduction in heat-transfer coefficient.

It follows from an analysis of the experimental and theoretical data that Eq. (2), taking account of the influence of variability in the thermophysical properties and the initial section, may be recommended for the calculation of heat transfer to supercritical-pressure helium in the given parameter range (A = 1-830 SI units; $P/P_{cr} \geq 1.05$).

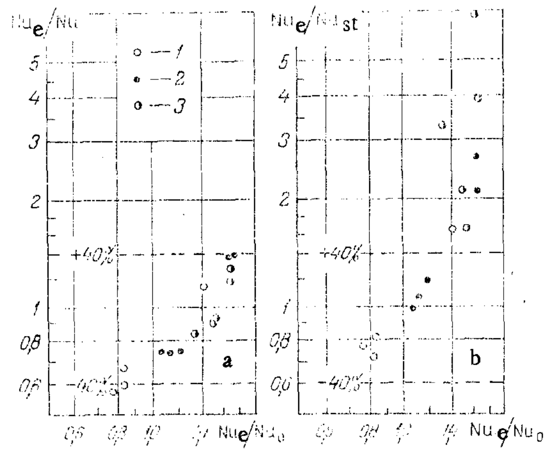

Fig. 3

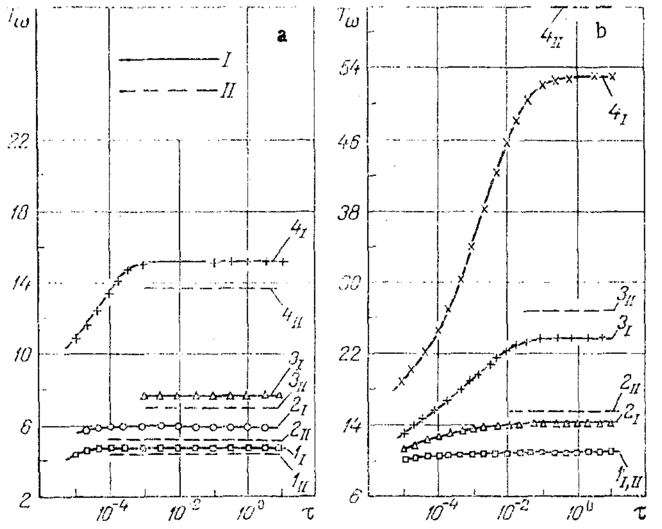

Fig. 4

Fig. 3. Results of generalizing the experimental data of [2]: a) Nu, calculation by Eq. (2); b) Nu_{st}, calculation by the equation of [11]. 1) Data for $A < 15$ SI units; 2) $15 < A < 100$ SI units; 3) $100 < A < 830$ SI units.

Fig. 4. Comparison of experimental and calculated – from Eq. (2) – wall temperatures at the stage of convective heat transfer in conditions of pulsed load: I) experimental profile of T_w [2]; II) profile of T_w calculated from Eq. (2). a) $q_w = 0.3 \cdot 10^4$ (1), 10^4 (2), $3 \cdot 10^4$ (3), 10^5 (4) W/m^2; b) 10^3 (1), 10^4 (2), $3 \cdot 10^4$ (3), 10^5 (4) W/m^2. a) $P = 0.25$ MPa, $\bar{T} = 4$°K, $Re = 7.7 \cdot 10^5$; b) 0.25, 9.9, $1.19 \cdot 10^5$. T_w, °K; τ, sec.

NOTATION

x, distance from the beginning of heating, m; q_w, specific heat flux, W/m^2; G, mass flow rate, kg/sec; ρu, specific mass flow rate, kg/sec·m^2; P, pressure, N/m^2; P_{cr}, pressure at critical point, N/m^2; $\bar{T}$, mean-mass temperature, °K; T_{in}, input temperature, °K; T_w, temperature of internal surface, °K; T_m, pseudocritical temperature, °K; H_w, enthalpy at T_w, J/kg; $\bar{H}$, c_p, ρ, μ, λ, β, enthalpy of the flow, specific heat, density, viscosity, thermal conductivity, volume-expansion coefficient at $\bar{T}$, respectively; Nu_e, experimental Nusselt number; Nu, theoretical Nusselt number; $A = q_w d^{0.2}/(\rho u)^{0.8}$, boundary-condition parameter, SI units; $Nu_0 = 0.023 Re^{0.8} Pr^{0.4}$; $T^* = \bar{T}$ when $\bar{T} < T_m$; $T^* = T_m$ when $\bar{T} > T_m$.

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EXPERIMENTAL STUDY OF HEAT EXCHANGE IN A MODERATELY RAREFIED GAS

A. N. Kulev, A. M. Shestakov, S. F. Borisov,
and Yu. G. Semenov

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An experimental study is performed of heat exchange in multiatomic gases at moderate Knudsen numbers in coaxial geometry. The data obtained are described well by the Liu–Lees theory of multiatomic gases.

The heat-exchange problem in rarefied gases has many practical applications, such as high-altitude aerodynamics, precision chemical technology, etc. On the other hand, comparison of experimental results on heat exchange obtained under conditions suitable for theoretical consideration of the problem provides valuable information on characteristics such as parameters of the intermolecular interaction potential and energy accommodation and tangential molecular momentum coefficients.

At present the character of heat exchange in the free molecular regime has been studied thoroughly [1, 2]. This is because it is possible to determine the energy accommodation coefficients characterizing energy exchange in the gas–solid system properly [3-5]. Heat exchange has been studied in greater detail in the continual limit [6, 7], since such studies are the major source of information on gas thermal conductivity coefficients. At the same time, experimental data for the region of transition between free molecular and continual regimes are few in number, especially for multiatomic gases.

There exist a large number of theoretical studies on heat exchange in planar geometry, based on solution of the Fourier equation using the temperature change condition on the boundary (see review [4]). However, such an approach does not permit description of the entire rarefaction range. This shortcoming can be eliminated only by solving Boltzmann's equation or a model thereof with substitution of proper boundary conditions.

Two studies are available [8, 9] in which heat exchange in monatomic gases was considered at arbitrary Knudsen number with the assumption of small temperature changes for the geometry met most often in practical applications – coaxial cylinders. Precise treatment of heat exchange in multiatomic gases is complicated by the necessity of introducing energy accommodation coefficients for the internal degrees of freedom. However, under conditions of complete molecular energy exchange with the surface such a description is possible by introducing into the solution some factor which considers the character of energy exchange in intermolecular interactions [10].

Below we will present results of experimental studies of thermal fluxes in certain mon- and multiatomic gases by the heated wire method at a temperature of about 300°K in the intermediate region (Kn = 0.01-1). Processing the data by the theory of [9], extended to multiatomic gases, allowed determination of the Eucken factor, which coincided with values avail-

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