LITERATURE CITED

1. Yu. V. Tsvetkov and S. A. Panfilov, Low-Temperature Plasmas in Reduction Processes [in Russian], Nauka, Moscow (1980).
2. A. A. Erokhin, Plasma-Arc Refining of Metals and Alloys [in Russian], Nauka, Moscow (1975).
3. V. I. Yavoiskii, G. A. Dorofeev, and I. L. Pavkh, Theory of Blowing of a Steelmaking Bath [in Russian], Metallurgizdat, Moscow (1974).
4. I. P. Ginzburg, V. A. Surin, A. A. Bagautdinov, A. S. Grigor'yants, and L. I. Shub, "Study of the discharge of a gas stream from a submerged nozzle into a liquid," Inzh.-Fiz. Zh., 33, No. 2, 213-233 (1977).
5. S. V. Zhurbin, V. P. Motulevich, and E. D. Sergievskii, "Heat transfer in the cooling of plasma jets by a liquid coolant," Eighth All-Union Conference on Low-Temperature-Plasma Generators, Summary of Documents, Vol. 1, ITF (Institute of Thermophysics), Novosibirsk (1980), pp. 114-117.

RELATIVE INCREASE IN HEAT TRANSFER IN VISCOUS-INERTIAL REGIMES OF FLOW OF HELIUM AT SUPERCRITICAL PRESSURE IN A HEATED PIPE

V. A. Bogachev, V. M. Eroshenko,
and L. A. Yaskin

UDC 536.24

Results are presented from an experimental study of an increase in heat transfer to a turbulent flow of supercritical helium in a pipe.

It follows from [1, 2] that, given sufficiently high heat fluxes on the wall, the heat-transfer rate in the forced turbulent pipe flow of supercritical helium can increase significantly in the case of heat exchange with constant liquid properties. According to the correlations in [3, 4], based in the region $\mathrm{Nu} > \mathrm{Nu}_0$ on limited data from [1], this effect is governed by the specific heat ratio $\bar{c}_p/c_{pq}$. No special conditions have been observed for a relative increase in heat transfer in the case of viscous-inertial regimes of flow of supercritical helium. The present work is devoted to experimental investigation of this question.

The experiments were conducted on a crystal-type unit. High-pressure helium traveled from a ramp through a reducer and a control valve into the liquid-nitrogen-filled cryostat. The helium was cooled in the cryostat in two heat exchangers to about 80°K by reflux flow of the helium with the vapors of the boiling nitrogen. The helium was then sent to an adsorber with activated charcoal where it was cleaned and dried. It then traveled along a cryogenic pipeline to a KG 60/300-1 cryostat with liquid helium. Here, it was first gradually cooled to 8-15°K in the main heat exchanger by refluxing with the liquid helium. Then it was cooled to 5-6°K in an intermediate heat exchanger by outgoing vapors from boiling helium. Finally, it was cooled in a liquid heat exchanger to 4.2°K. The supercooled helium entered a vertical section located in a vacuum chamber submerged in liquid helium. The reverse helium flow, after throttling and heating, was passed through a metering section with a ring and then directed into a gas holder.

The working section was a stainless steel pipe 1.8 mm in diameter, 510 mm in length, and 0.1 mm in wall thickness. It had a heated section 400 mm (222 diameters) long which preceded the 78-mm-long unheated hydrodynamic stabilization section. The walls of the pipe were heated by the passage of a direct electrical current through them from niobium stannide leads. The wall temperature was measured at 15 stations along the working section with TSG-2 germanium resistance thermometers installed 25 mm (about 14 diameters) apart in holders made of electrolytic copper. The holders were secured tightly against the heated pipe through a lavsan film 10 μm thick. The mean-mass temperature of the helium at the inlet and outlet of the working section was measured with similar thermometers installed in mixing chambers. The temperature of the outer

---

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 44, No. 4, pp. 544-548, April, 1983. Original article submitted January 4, 1982.

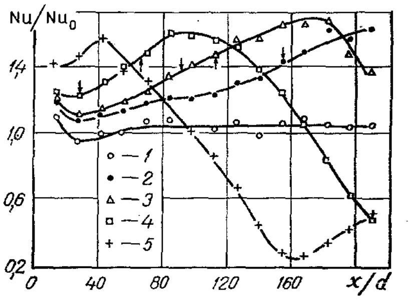

Fig. 1. Change in relative heat transfer along a pipe with different thermal loads: $p = 0.246$-0.248 MPa; $T_{in} = 4.241$-4.248°K; $G = 0.25$ g/sec; 1) $q = 187\ W/m^2$; 2) 804; 3) 1000; 4) 1280; 5) 1850; $Re_{in} = 5.2\cdot 10^4$; $\downarrow$) section with $T_w = T_m$; $\uparrow$) section with maximum $\bar{c}_p/c_{pq}$.

surface of the pipe was determined from measurements of the wall temperature and heat flux and data on the thermal conductivity of the stainless steel from [1]. The pressure was measured with a standard manometer with 0.003-MPa graduations.

The potential difference on the resistance thermometers was measured with an F-30 digital voltammeter, while the current through the thermometers was determined from the voltage drop on a standard resistance. In the absence of a thermal load, the measured wall temperatures were located in the range ± 0.002°K relative to the temperature of the helium at the inlet. When the pipe was heated, the heat balance agreed with an accuracy no worse than 5%. The reproducibility of the experimental data on the heat-transfer coefficient was within the range ±5%. In regimes with slight variation of the helium properties across the flow, heat transfer was described to within about 10% by the equation of Petukhov and Kirillov [5], which served as proof of the reliability of the experimental data obtained.

The experiments were conducted with a rising helium flow in the following parameter ranges: $p = 0.23$-0.30 MPa, $T_{in} = 4.21$-4.24°K $< T_m$; $G = 0.19$-0.26 g/sec and $q = 100$-$1850\ W/m^2$. The local Reynolds numbers ranged from $3.6\cdot 10^4$ to $9.0\cdot 10^4$. The parameter Gr/Re^2 was $\lesssim 10^{-2}$, which allowed us to classify the investigated heat-transfer regimes as viscous-inertial, i.e., without the effect of free convection [6]. We investigated 48 regimes altogether, corresponding to 720 empirical points.

The following was established regarding the stability of the heat-transfer regimes. As long as the local temperature of the liquid within the heated section was below the pseudocritical value T_m, the readings of the resistance thermometers and manometer were marked by their high stability. When the temperature T_m was first reached in the boundary layer of the liquid, at the pipe outlet, weak low-frequency wall-temperature fluctuations generally occurred. These fluctuations increased as the thermal load increased and the zone of the temperature T_m shifted away from the wall and upstream. Finally, when the mean-mass temperature of the liquid at the outlet reached T_m, the readings of the outlet thermometer and manometer – which sensed the pressure at the inlet of the working section – began to undergo low-frequency oscillations. In such regimes, the pseudocritical-temperature zone crossed the entire flow field, from the wall at the inlet to the core of the flow at the outlet. A further increase in electrical power led to such strong oscillations of all of the measured temperatures (except the inlet temperature) and pressure that measurements became impossible.

The measurements were analyzed on an ES-1033 computer with a program for calculating the thermophysical properties of helium [7] using the data in [8]. The heat-transfer characteristic employed was the ratio of the local Nusselt number to Nu_0, calculated with the equation of Petukhov and Kirillov the case of constant liquid properties. The thermophysical properties in the Nu, Re, and Pr numbers were determined from the mean-mass temperature of the helium in cross section.

Figure 1 shows typical curves of the change in relative heat transfer along the pipe with different heat fluxes on the wall. It is apparent that at first an increase in q leads to a monotonic increase in Nu/Nu_0 within the entire heated part except for the thermal initial section (regime 2). A distinct maximum (regimes 3-5) in the distribution of relative heat transfer appears beginning with a certain thermal load. This maximum is located quite a bit downstream from the section where the wall temperature T_w is equal to the pseudocritical temperature of the helium T_m (this is designated in the figure by a downward arrow). It should be noted that the difference between T_w and T_m in the section with maximum relative heat transfer may reach 0.2°K. The maximum moves upstream with an increase in q, the value of the maximum changing little. Passing through the maximum, the ratio Nu/Nu_0 begins to smoothly decrease and, at certain values of q, passes into the region of Nusselt numbers lower than Nu_0. It finally reaches a minimum at $T_q \approx T_m$, after which the section of increasing relative heat transfer (regime 5) begins again. The results obtained here show that the distribution of Nu/Nu_0 along a pipe may be sinusoidal if the pipe is long enough and the temperature of the liquid at the inlet is below T_m.

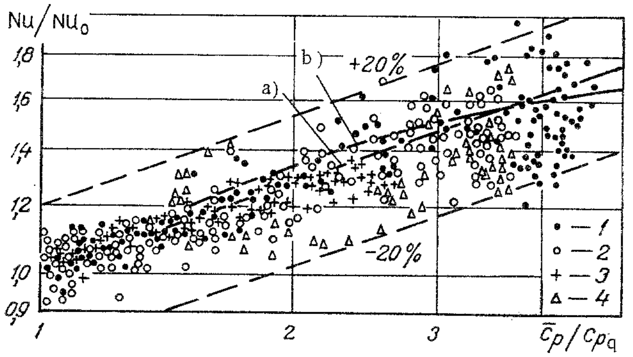

Fig. 2. Relative increase in heat transfer in relation to the specific heat ratio $\bar{c}_p/c_{pq}$: 1) p = 0.23 MPa; 2) 0.25; 3) 0.30 (our experiment); 4) [1], p = 0.25 MPa; a) Eq. (1); b) Eq. (2).

Analysis of the experimental data shows that in the region $Nu/Nu_0 > 1$ the distribution of relative heat transfer along the pipe roughly follows the change in the ratio of specific heats $\bar{c}_p/c_{pq}$, i.e., an initial increase to a maximum and a subsequent decrease to unity. This fact can be explained by analyzing heat transfer in the boundary region of the flow, where there is a fundamental change in the temperature of the liquid. If we ignore the change in the total heat flux near the wall [9] and do not consider the contribution of the molecular mechanism to the heat transfer, we obtain

$$q \approx q_t = -\mu c_p \frac{1}{\mathrm{Pr}_t} \frac{\varepsilon_m}{\nu} \frac{\partial T}{\partial y}.$$

In the investigated range of parameters with $Nu/Nu_0 > 1$, the change in absolute viscosity μ across the flow is slight compared to the change in specific heat c_p, while the flow was not sufficiently isothermal ($\rho_q/\rho_w < 3$, $\psi = 1 + \beta_q(T_w - T_q) < 2$, $T_w/T_q < 1.1$) to have an appreciable effect on the distribution of the dimensionless coefficient of turbulent transport ε_m/ν. We then find from the above expression for heat flux that, in this case, an increase in c_p near the wall should lead to a reduction in the temperature gradient in the boundary layer, i.e., to a decrease in wall temperature and an increase in heat transfer relative to quasiisothermal conditions at the level T_q. We took $\bar{c}_p = (h_w - h_q)/(T_w - T_q)$ as the expression for the mean specific heat of the liquid layer, which determines the heat transfer. It should be noted that the maximum of the dimensionless parameter $\bar{c}_p/c_{pq}$ is located between the sections with $T_w = T_m$ and the maximum ratio Nu/Nu_0 (this location is denoted in Fig. 1 by an upward arrow).

The above provides a basis for representing data on heat transfer in the region $Nu/Nu_0 > 1$ in the form of a dependence on the ratio of the specific heats $\bar{c}_p/c_{pq}$. Such a generalization was first made for supercritical liquids (CO_2 and H_2O) by Protopopov [10], who obtained the equation

$$\mathrm{Nu}/\mathrm{Nu}_0 = (\bar{c}_p/c_{p_q})^{0.35}. \tag{1}$$

In a similar correlation for helium [4], the exponent was equal to 0.28. A single-valued relation is obtained between the ratio Nu/Nu_0 and the parameter $\bar{c}_p/c_{pq}$ at low $T_w/T_q < 1.1$ with the following equation for supercritical helium from [3], which in the present case can be represented by an asymptotic expression

$$\mathrm{Nu}/\mathrm{Nu}_0 = 2/(1 + c_{p_q}/\bar{c}_p). \tag{2}$$

It must be kept in mind that the value of Nu_0 in the equations in [3, 4] was calculated from the Dittus–Bolter relation.

Figure 2 shows all of the data we obtained for $Nu/Nu_0 > 1$, as well as the experimental results from [1]. It can be seen that all of the experimental points are grouped around curves described by Eqs. (1) and (2). The scatter of the data relative to Eq. (1) is ±20%. We also found that the equation in [4] is sufficiently accurate.

The heat-transfer regimes investigated with $Nu > Nu_0$ should be interpreted as "normal" [9] rather than "improved," since the heat-transfer coefficient and wall temperature in the regimes changed monotonically along the pipe, and the pattern of change in Nu/Nu_0 can be explained on the basis of common representations of the heat-transfer mechanism in turbulent flows.

The results of the completed study allow us to conclude that, with values $\bar{c}_p/c_{pq} > 1$, heat transfer in viscous-inertial regimes of supercritical helium flow can be calculated either from the equations recommended in [4] or from the equation (1) of V. S. Protopopov.

NOTATION

T, temperature; p, pressure; G, flow rate; q, heat flux; ρ, density; h, enthalpy; c_p, specific heat at constant pressure; β, coefficient of cubical expansion; μ, absolute viscosity; ν, kinematic viscosity; d, diameter; Nu, Nusselt number; Pr, Prandtl number; Re, Reynolds number; $Gr = g\beta d^3(1 - \rho_c/\rho_l)/\nu_l^2$, Grashof number. Indices: w, wall; q, liquid, mean-mass value; 0, constant properties; t, turbulent; m, pseudocritical value; in, inlet.

LITERATURE CITED

1. P. J. Giarratano and M. C. Jones, "Deterioration of heat transfer to supercritical helium at 2.5 atm," Int. J. Heat Mass Transfer, 18, No. 5, 649-654 (1975).
2. L. A. Yaskin, M. C. Jones, V. M. Yeroshenko, et al., "A correlation for heat transfer to supercritical helium in turbulent flow in small channels," Cryogenics, 17, No. 10, 549-552 (1977).
3. V. M. Yeroshenko and E. V. Kuznetsov, "Calculating heat transfer and drag in a flow of helium in the near-critical thermodynamic state," in: Superconducting Transmission Lines [in Russian], Moscow Power Engineering Institute (1979), pp. 65-74.
4. V. M. Yeroshenko and L. A. Yaskin, "Applicability of various correlations for the prediction of turbulent heat transfer of supercritical helium," Cryogenics, 21, No. 2, 94-96 (1981).
5. B. S. Petukhov and V. V. Kirillov, "Heat exchange in the turbulent flow of a liquid in pipes," Teploenergetika, No. 4, 63-68 (1958).
6. V. S. Protopopov, "Generalizing relations for local heat-transfer coefficients in the turbulent flow of water and carbon dioxide at supercritical pressure in uniformly heated circular pipes," Teplofiz. Vys. Temp., 15, No. 4, 815-821 (1977).
7. A. M. Baron, "Pack of applied programs for calculating the thermophysical properties of helium-4 in a broad range of state parameters," in: Methods of Calculating the Thermophysical Properties of Working Substances and Heat Carriers in the Comprehensive Optimization of Heat and Power Plants [in Russian], SIÉ Sib. Otd. Akad. Nauk SSSR, Irkutsk (1978), pp. 143-146.
8. R. D. McCarty, "Thermophysical properties of helium-4 from 2 to 1500°K with pressures to 1000 atm," NBS Technical Note 631 (1972).
9. B. S. Petukhov, "Heat transfer and friction in turbulent pipe flow with variable physical properties," in: Advances in Heat Transfer, Vol. 6, Academic Press, New York (1970), pp. 504-564.
10. V. S. Protopopov, "Investigation of convective heat transfer in the single-phase near-critical region," Author's Abstract of Doctoral Dissertation, Engineering Sciences, Moscow Power Engineering Institute (1975).