ENTRANCE SECTION HEAT TRANSFER IN FLOW OF HELIUM AT SUPERCRITICAL PRESSURE

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It is shown that heat transfer in the entrance section depends on the flow parameters (inlet pressure and temperature), distance from the inlet, and gas heating level.

It is known that turbulent flow in the entrance section differs appreciably from stabilized flow, and this causes a difference of the heat-transfer coefficients. In turn, the strongly nonisothermal conditions influence the heat transfer appreciably. This shows up as a relatively large increase of heat transfer in the entrance section, compared with the heat transfer in the section with quasistabilized heat transfer, i.e., with conditions independent of the inlet conditions, and as an increase of the entrance section length, which can extend up to $x/d \approx 50$ [1].

Substantially more complex heat-transfer laws are observed for heat-transfer agents at supercritical pressure (SCP) in the case of heating of a liquid to pseudocritical temperature (T_m) in the entrance section. Such heat-transfer regimes were noted, for example, in [2]. In the "degraded" heat-transfer conditions in the region $\bar{T} \approx T_m$ in the entrance section the authors did not observe stabilization of heat transfer, which is associated with the influence of the "prehistory" of the process: at ordinary values of ρu, q_w, and $\bar{H}$ the heat transfer depended on the length of the previously heated section [3]. It should be noted that the sparse available test data did not afford a full representation of the heat-transfer laws under these conditions, and could not form a basis for design recommendations.

To study the laws of heat transfer to heat-transfer agents at SCP in the entrance section under strongly nonisothermal conditions, investigations were carried out with forced convection of helium at SCP in a horizontal tube.

The model was a stainless steel tube of internal diameter d = 1.4 mm and heated section length L = 545 mm. Ahead of the heated section there was a hydrodynamic settling section of length L = 50d. The wall temperature was monitored from the mean of the tube generators at distances x/d = 11, 18, 28, 32, 40, 50, 61, 75, 93, 114, 140, 182, 239 from the beginning of the heated section. The layout of the experimental facility was given in [4].

The experiments were conducted over a range of the regime parameters: $P = 0.24\text{-}0.68 \cdot 10^6$ 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, $\bar{T}_{in} = 4.41\text{-}7.1$°K, $\bar{T}/T_m = 0.8\text{-}6$, A = 10-100 SI units.

The region of variation of the working parameters was chosen so that one could conduct investigations under "normal" ($Nu/Nu_0 \approx 1$), "enhanced" ($Nu/Nu_0 > 1$), and "degraded" ($Nu/Nu_0 < 1$) heat-transfer conditions. In the experiments the flow bulk temperature was both less than, and greater than the pseudocritical temperature T_m. Here T_m in most regimes was located at the start of the heated section, due to the relatively high helium inlet temperatures $(\bar{T}_{in})_{min} = 4.41$°K, and the large gas heating levels (A up to 100 SI units). From the experimental investigation it was noted that if $\bar{T} \approx T_m$ was attained in the section $x/d < 50$ at a comparatively high level of nonisothermal conditions, one observed regimes with an anomalous heat-transfer variation in the entrance section (Fig. 1), analogous to that noted in [2].

To evaluate the influence of the entrance section on heat transfer one must have a relation that correlates the test data in the section of quasistabilized heat transfer over a wide range of variation of the boundary conditions, including high heating levels of the cooling agent (large A). For this purpose we compared the theoretical results from a number of equa-

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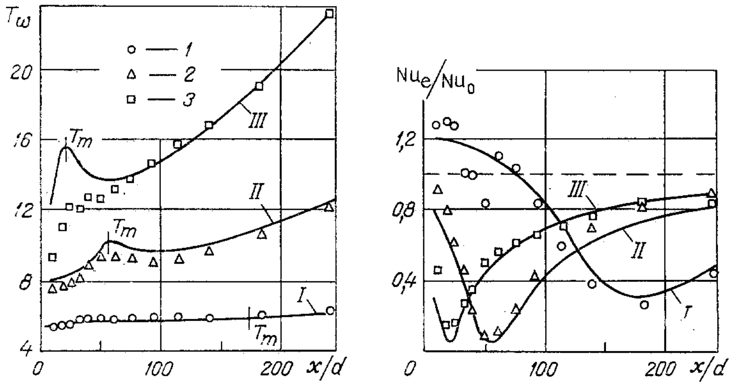

Fig. 1. Variation of the wall temperature T_w and the heat transfer along the model with increase of the heating level ($P = 0.25 \cdot 10^6$ N/m²): 1) A (SI units) = 11; 2) 31; 3) 51; I, II, III) increase of T_w according to Eq. (1) for regimes 1-3, respectively; Nu_{th}) calculated from Eq. (1); T_m is the position $\bar{T} \approx T_m$.

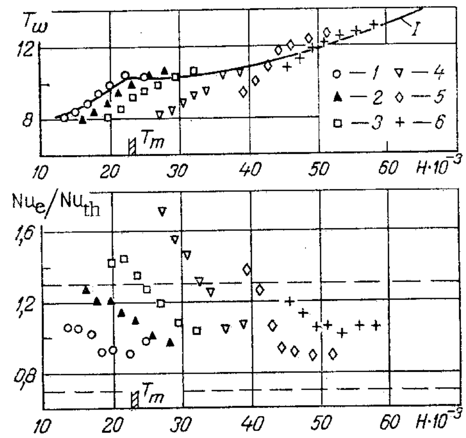

Fig. 2. Influence of inlet temperature on heat transfer in the section x/d < 100 ($P = 0.3 \cdot 10^6$ N/m², A ≈ 35 SI units): 1) A (SI units) = 34, $\bar{T}_{in}$ (°K) = 4.41; 2) 35 and 4.89; 3) 36 and 5.3; 4) 34 and 5.61; 5) 35 and 6.35; 6) 37 and 7.1; I) calculation of T_w from Eq. (1); Nu_{th}) calculated from Eq. (1); T_m is the position of $\bar{T} \approx T_m$.

tions with the authors' test data, and also with the data of [5-7]. The most successful correlation (to an accuracy in the range ±25% with boundary conditions of the second kind) for the active mass of test data for the "enhanced," "degraded," and "normal" heat-transfer conditions was obtained when one used the relation [8]:

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

where m = 0.6.

It is known that the greatest variation of heat transfer along a channel in the flow of a medium at supercritical pressure is observed in the region of the pseudocritical temperature T_m. An increase of the heating level (of parameter A) initiates the appearance of regimes characterized by substantially reduced heat transfer ($Nu_e/Nu_0 \ll 1$) and the appearance of temperature "peaks" (Fig. 1). It follows from analysis of the test results that this law, which is valid in the sections of quasistabilized heat transfer, is not observed always (Fig. 1). This is seen especially on arrival of the section with $\bar{T} \approx T_m$ at the section x < 50d. Here the wall temperature "peaks" are smoothed, although as a rule the relative heat transfer

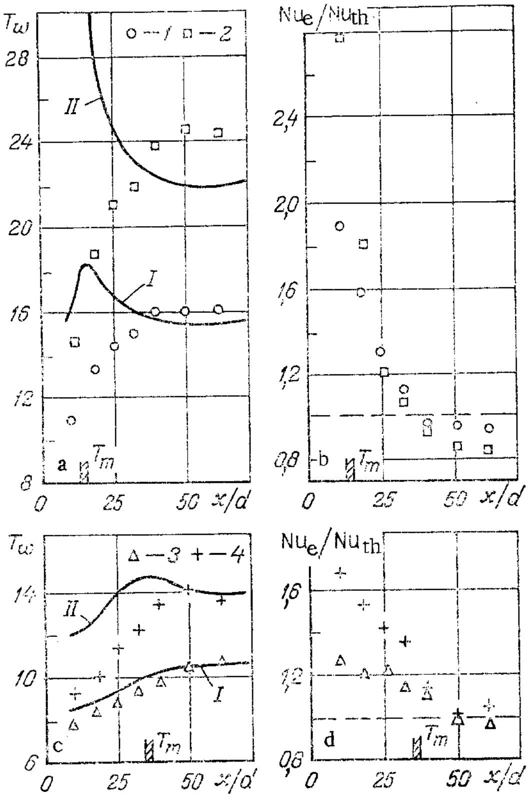

Fig. 3

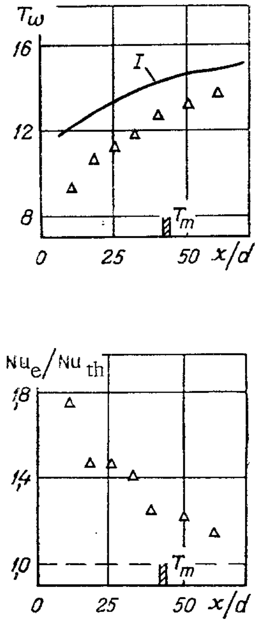

Fig. 4

Fig. 3. Influence of heating level on the heat transfer: a, b) $P = 0.25 \cdot 10^6$ N/m²; 1) A (SI units) = 60; 2) 92; c, d) $P = 0.3 \cdot 10^6$ N/m²; 3) A (SI units) = 35; 4) 53; I, II) T_w calculated from Eq. (1); Nu_{th}) calculated from Eq. (1); T_m is the position of $\bar{T} \approx T_m$.

Fig. 4. Variation of heat transfer for $P = 0.6 \cdot 10^6$ N/m² (A = 56.4 SI units): I) T_w calculated from Eq. (1); Nu_{th}) as calculated from Eq. (1); T_m is in the position $\bar{T} \approx T_m$.

$Nu/Nu_0 < 1$. At a comparatively low heating level (A < 15 SI units) the nature of the heat-transfer variation in the entrance section corresponds to the ordinary law for quasiisothermal heat transfer

$$Nu_e = \varepsilon_l Nu_{th}, \tag{2}$$

where ε_l is a correction accounting for the variation of heat transfer in the entrance section in quasiisothermal conditions.

For $\bar{T}_{in} < T_m$ with increase of $\bar{T}_{in}$ the relative heat transfer ($Nu^* = Nu_e/Nu_{th}$) in the entrance section increased and reached a maximum for $\bar{T}_{in} = T_m$ (Fig. 2). Here the length of the entrance section in which we noted an increase of Nu^* (within the accuracy of the Eq. (1) correlation) could reach up to 50d. For $\bar{T}_{in} > T_m$ with increase of $\bar{T}_{in}$ we observed reduced relative heat transfer and a simultaneous decrease of the length of the entrance section to 20d. For $x/d > 50$ the variation of the helium inlet temperature for any boundary conditions and flow parameters had no noticeable influence on the heat transfer (Figs. 1 and 2).

The nature of the heat-transfer variation in the entrance section and the section length depend on many factors: the initial temperature, the heating level, and the position of the section with $\bar{T} = T_m$ relative to the start of the heating section. Figure 3a,b shows the variation of wall temperature and of heat transfer for two heated regimes in the "degraded" heat-transfer case ($(Nu_e/Nu_0)_{min} = 0.09$ and 0.06 from Eq. (1)), differing in heating level from one another by a factor of 1.5. For these regimes the initial temperatures were chosen so that the distances x_m to the sections with temperature $\bar{T} = T_m$ would be approximately the same ($x_m = 14.3d$). An increase of the heating level leads to an increase of the relative heat-transfer coefficient Nu^* in the first section by a factor of 1.5. As the distance from the entrance increases the difference between Nu* for the different regimes reduces, and at a distance $x > 40d$ the heat transfer coincides with the values for quasistabilized heat transfer, within the limits of accuracy of Eq. (1).

As x_m increases, the influence of the entrance section is propagated to a greater distance from the inlet (up to 50d) (Fig. 3c, d). Here the increase of the heat transfer Nu^* is somewhat less than the increase of the heating level. In comparison with the test data in Fig. 3a b this relative decrease of heat transfer (Nu*) with increase of x_m can be explained in part by the variation of the thermophysical properties of helium as the flow temperature goes further from $\bar{T} = T_m$, which leads to an increase of the heat-transfer coefficient Nu_{th}/Nu_0 in the case of quasistabilized heat transfer.

With increase of pressure the length of the entrance section increases for the same heating levels (Fig. 3c, d and Fig. 4). Here the dependence of heat transfer Nu* on the value of x_m decreases. The nature of the variation of the relative heat transfer Nu* with entrance section length remains the same: there is a maximum near the start of the heated section and a gradual decrease to the quasistabilized values. Here the variation of heat transfer Nu* in the entrance section at comparatively high pressures depends more on the gas heating level than on x_m.

It follows from analysis of the test data that the characteristic variation of the thermophysical properties of helium at supercritical pressure near pseudocritical temperatures, which causes "degraded" heat-transfer regimes with increase of heating level, has considerably less influence in the entrance section. Here the heat transfer in the entrance section in the region $\bar{T} = T_m$ under strong nonisothermal conditions is subject to complex laws and depends on x/d, on the flow parameters (inlet temperature and pressure), and the gas heating level. The length of the entrance section in which one observes an increase of heat transfer compared with the value under quasistabilized conditions, is variable and can reach 50d.

NOTATION

x, distance from the start of heating, m; q_w, specific heat flux, W/m²; G, mass flow rate, kg/sec; ρu, specific mass flow rate, kg/sec·m²; P, pressure, N/m²; P_{cr}, pressure at the critical point, N/m²; $\bar{T}$, bulk temperature, °K; T_{in}, inlet temperature, °K; T_w, temperature of the inside surface, °K; T_m, pseudocritical temperature, °K; H_w, enthalpy at T_w, J/kg; $\bar{H}$, c_p, ρ, μ, λ, β) respectively heat, density, viscosity, thermal conductivity, and volume expansion coefficient at $\bar{T}$; $\psi = T_w/\bar{T}$, temperature factor; Nu_e, experimental value of the Nusselt number; Nu_{th}, calculated value of the Nusselt number; $A = q_w d^{0.2}/(\rho u)^{0.8}$, parameter describing the regime of the boundary conditions, SI units; $Nu_0 = 0.023Re^{0.8}Pr^{0.4}$, $T^* = \bar{T}$ for $\bar{T} < T_m$, $T^* = T_m$ for $\bar{T} > T_m$.

LITERATURE CITED

1. V. A. Kurganov, "Investigation of heat transfer in tubes to monatomic and polyatomic gases with variable properties," Author's Abstract of Candidate's Dissertation, Technical Sciences, Moscow (1971).
2. B. S. Petukhov, V. A. Kurganov, and V. B. Ankudinov, "Heat transfer and hydraulic drag in tubes in turbulent flow of a liquid with near critical state parameters," Teplofiz. Vys. Temp., 21, No. 1, 92-100 (1983).
3. V. B. Ankudinov, "Experimental investigation of the drag and heat transfer in turbulent flow of a liquid with supercritical parameters in tubes," Author's Abstract of Candidate's Dissertation, Technical Sciences, Moscow (1982).
4. M. A. Valyuzhinich and E. V. Kuznetsnov, "Experimental investigation of heat transfer in heating of helium at supercritical pressure," Report in VINITI, No. 4708-82, Sept. 1, 1982.
5. P. J. Giarratano, V. D. Arp, and R. V. Smith, "Forced convection heat transfer to supercritical helium," Cryogenics, 11, No. 5, 385-393 (1971).
6. H. Ogata and S. Sato, "Measurements of forced convection heat transfer to supercritical helium," Proc. 4th Int. Cryogenic Eng. Conf., Eindhoven, The Netherlands, May 24 (1972), pp. 291-294.
7. 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, 649-653 (1975).

8. V. M. Eroshenko and E. V. Kuznetsov, "Analysis of heat transfer in heating of helium in the supercritical thermodynamic state in forced convection conditions," in: Heat and Mass Transfer in Boiling and Flow of Cryogenic Liquids [in Russian], ITMO Acad. Sci. BSSR, Minsk (1980), pp. 33-49.

TRANSITION TO FILM BOILING OF HELIUM UNDER STEPPED THERMAL LOADING

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The results of an experimental investigation of the transition to film boiling of helium under stepped thermal loading, obtained in a wide range of pressures, are presented.

The critical point of heat transfer accompanying nonstationary boiling of helium does not appear immediately after thermal loading, but rather after some time τ_{cr}, during which the intensity of the heat transfer remains quite high [1-4]. The length of time indicated is of considerable interest for calculations of the stability of superconducting magnets under pulsed thermal loads [5].

In this work we studied the effect of a heat flow q and saturation pressure p on the value of τ_{cr} during boiling of liquid helium in a large volume under conditions of a jump in the intensity of heat efflux from the heated wall. As a test element we used a 65 × 4 × 0.05 mm working section of a brass foil described in [6]. The experiments were performed under the saturation pressure of helium 40-200 kPa with different orientation of the heat transfer from the surface in the field of gravity.

The value of τ_{cr} was determined from the oscillograms of the nonstationary thermal process (Fig. 1), on which the change in the working current of the heater I and the overheating of the wall of the test element ΔT were recorded simultaneously. The onset of film boiling was conditionally taken as the time when the overheating of the wall became 30% higher than the value corresponding to nonstationary bubble boiling of helium. As is evident from Fig. 1, in the course of almost the entire time τ_{cr} the temperature of the wall remains practically constant, with the exception of small intervals of time at the beginning of the transient process and prior to the onset of film boiling. Thus, within the time τ_{cr} the amount of heat expended on heating the working section can be ignored, and the heat flux density on the heat-exchange surface can be defined as $q \approx Q/F$.

The experiments showed that τ_{cr} depends in a complicated manner on the thermal load, pressure, and orientation of the heating surface. Figure 2 shows in the $q-\tau_{cr}$ plane the experimental data, obtained with different angles of inclination of the heating surface to the horizontal under pressures close to atmospheric pressure. Analogous results were also ob-

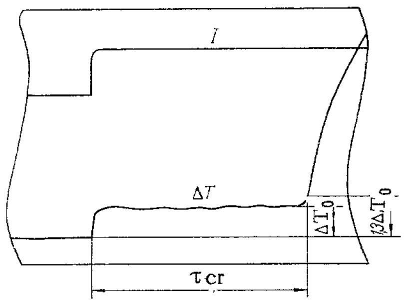

Fig. 1. Oscillogram of the nonstationary thermal process.

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