transfer and hydraulic resistance; q_V, volume density of energy release; λ_{ef}, ν_{ef}, effective coefficients of heat conduction and viscosity; V, volume; ℓ, bundle length. Indices: s, solid phase; n, nonstationary; qs, quasistationary; b, average-mass; m, modified.

LITERATURE CITED

1. B. V. Dzyubenko, G. A. Dreitser, and L.-V. A. Ashmantas, Nonstationary Heat-and-Mass Exchange in Bundles of Twisted Tubes [in Russian], Moscow (1988).
2. B. V. Dzyubenko, L.-V. A. Ashmantas, M. D. Segal', and A. B. Bagdonavichyus, Izv. AN Énergetika i Transport, No. 4, 131-138 (1987).
3. B. V. Dzyubenko and V. N. Stetsyuk, Inzh.-Fiz. Zh., 55, No. 5, 709-715 (1988).
4. B. V. Dzyubenko, L.-V. A. Ashmantas, and A. B. Bagdonavichyus, Inzh.-Fiz. Zh., 55, No. 3, 357-363 (1988).
5. B. V. Dzyubenko, A. V. Kalyatka, V. I. Rozanov, and M. D. Segal', Inzh.-Fiz. Zh., 59, No. 4, 641-648 (1990).
6. B. V. Dzyubenko, L.-V. A. Ashmantas, and A. B. Bagdonavichyus, Inzh.-Fiz. Zh., 56, No. 1, 5-11 (1989).
7. E. O. Adamov, V. P. Smetannikov, A. S. Koroteev, et al., Special Anniversary Conf. "Nuclear Energetics in Space," Part 1. Reports of Soviet Specialists [in Russian], Obninsk (1990), pp. 11-14.

IMPROVED HEAT TRANSFER AT SUPERCRITICAL
PRESSURES OF ORGANIC HEAT-TRANSFER AGENTS

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It was found that under certain experimental conditions with increasing heat flux the temperature t_w of the wall of the heat-transfer tube decreases to values below the critical temperature of the liquid under study.

In order to switch to heat-exchangers operating with heat-transfer agents at supercritical pressures, the operation of such exchangers must be studied carefully and in detail in order to provide scientific-research and design organizations with reliable data on convective heat transfer at supercritical pressures of the heat-transfer substances and different conditions in a wide range of values of the process parameters. In this connection, in the present paper we present some results of experimental investigations of heat transfer in the case of flow of organic heat-transfer agents in a tube under supercritical pressures. The experiments were performed on the apparatus described in [1]. The experimental section consisted of an OKh18N10T stainless steel tube with an inner diameter of 2.09 mm, wall thickness of 0.46 mm, and heated length of 220 mm. The tube was heated by passing through it ac current at low voltage. The maximum error in the determination of the heat-transfer coefficient was equal to 14%.

We shall examine, for the example of n-heptane (P = 2.736 MPa, t_{cr} = 267.01°C), the temperature of the tube wall as a function of the heat-flux density. Figure 1 shows such curves for ascending motion of a liquid at supercritical pressures and constant mass velocity and temperature of the liquid at the input. Comparing the two curves shows that up to $t_w \approx t_m$ the experimental points for different pressures fall quite well on the same straight line. For $t_w \gtrsim t_m$ the curves diverge. On the sections B'C' and BC the divergence will be determined by the difference of the pseudocritical temperatures, while on the sections C'D' and CD the temperature difference increases with increasing heat-flux density. It should be noted that for processes with the same values of ρW and t_{liq}^{in} and different pressures the appearance of a secondary state of improved heat transfer corresponds to approximately the same value of the heat-flux density (q $\approx$ 3.0-3.1 MW/m²). Investigations showed that the drops in the wall temperature on the section DE at different pressures are

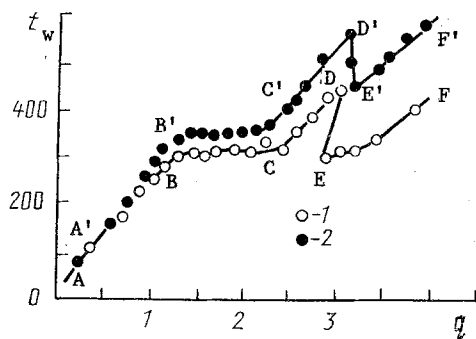Fig. 1. Dependence $t_w = f(q)$ for ascending motion of n-heptane at pressures of P = 4.5 MPa (1) and 5.0 (2).

also approximately the same, and for the cases studied they are equal to 130-140°C. At the indicated pressures the pseudocritical temperatures are equal to 304 and 312°C, respectively. The values of the pseudocritical temperatures were determined from experimental data on the isobaric heat capacity obtained in [2] for n-heptane.

The curves $t_w = f(q)$ presented in Fig. 1 were constructed from indications of thermocouples, placed at a distance x/d = 62.4 from the entrance into the tube. In order to get a complete idea of the character of the change occurring in the dependence of the wall temperature on the heat-flux density, it is useful to construct plots of the dependence from indications of thermocouples placed at different distances from the tube entrance. The results of one such measurement at P = 4.5 MPa and ρW = 2000 kg/(m²·sec) in the form $t_w = f(q)$ are presented in Fig. 2a. One can see from this figure that under conditions of ascending motion of n-heptane the character of the change in the plots is different for different distances from the tube entrance: for distance x/d = 76.8 from the tube entrance the change in the curve is similar to the dependences illustrated in Fig. 1, while at x/d = 19.4, 33.7, and 48.0 the wall temperature decreases appreciably on the section BC, in spite of the increase in the heat-flux density. It is sufficient to note that at these distances the wall temperature did not increase for heat-flux densities from ∿ 1.40 to ∿ 2.40 MW/m², but rather the temperature dropped by an amount of the order of 40°C. In addition, at distances x/d = 19.4, 33.7, and 48.0 from the tube entrance, for high values of the heat-flux density and high wall temperature no abrupt drop in the wall temperature was observed and on the sections BC and DEF the change in the curve was of the same character.

Figure 2b shows the wall temperature as a function of the heat-flux density for turbulent flow and with descending motion of n-heptane. The curves were constructed from indications of thermocouples placed at distances x/d = 17.7, 32.0, 46.4, and 75.0 from the tube entrance. Analysis of the data obtained show, that in sections located at x/d < 60.8, after the wall temperature reaches the pseudocritical temperature of the liquid under study, it also decreases with increasing heat-flux density. For example, the wall temperature is equal to 318°C at heat flux density 1.50 MW/m² and 228°C at 2.30 MW/m², i.e., when the heat-flux density increases by 0.8 MW/m² the wall temperature decreases by 90°C. In addition, for descending motion of n-heptane, at the indicated distances the minimum wall temperatures, occurring with q ≈ 2.25 MW/m², corresponding to improved heat transfer, are lower than the critical temperature of the liquid under study.

This character of the change in the dependence $t_w = f(q)$ for x/d < 60 was found only with a vertical position of the tube. It is confirmed by the results of investigations with horizontal and inclined positions of the tube (see Fig. 3). One can see that in all cases studied, when the wall temperature reached the pseudocritical temperature of the liquid under study, the temperature curve changes and heat transfer improves, i.e., as the heat-flux density increases the wall temperature at first decreases and then increases comparatively slowly and once again approaches the temperature corresponding to the maximum heat capacity of the liquid under study. For example, it is sufficient to note that with heat flux densities of 1.20 and 3.20 MW/m² the wall temperatures are approximately the same, i.e., increasing the heat-flux density by ∿ 2.00 MW/m² did not result in an increase in the wall temperature, rather in the indicated range of heat-flux densities the temperature decreased from ∿ 300 to ∿ 228°C. Comparing the results obtained shows that the character of the changes in the plots $t_w = f(q)$ is identical for the conditions studied — in many cases the experimental points even merge. It is not difficult to see that in a given section the experimental points fall between two bounding lines, obtained, correspondingly, with descending motion of the liquid for vertical and horizontal positions of the tube. In the region of improved
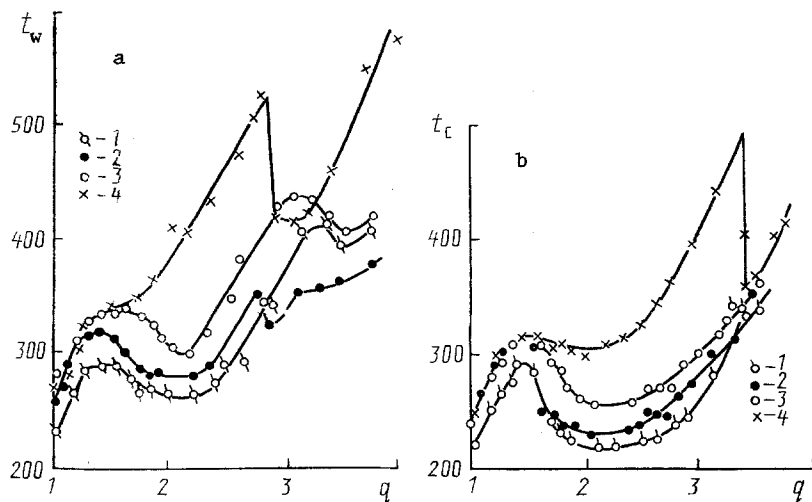
Fig. 2. Dependence $t_w = f(q)$ for ascending (a) and descending (b) motion of n-heptane: 1) $x/d = 19.4$; 2) 33.7; 3) 48.0; 4) 76.8; b) 1) $x/d = 17.7$; 2) 32; 3) 46.4 and 4) 75.0.
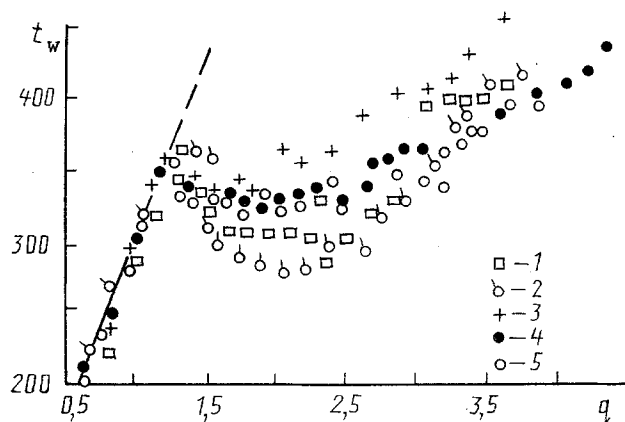

Fig. 3. Dependence $t_w = f(q)$ for n-heptane with P = 4.5 MPa and $x/d = 32$ from the tube entrance: 1, 2) ascending and descending motion, respectively; 3) horizontal tube; 4, 5) inclined tube with $\varphi = 30$ and $60°$, respectively.

heat transfer, the fact that the wall temperatures with descending motion of the liquid are lower than for other positions of the tube, for the same value of the heat-flux density, suggests that free convection can affect heat transfer. It should be especially noted that a decrease in the temperature of the heat-emitting surface in the critical region was also recorded previously in [3].

Thus the results of our experimental investigations show that irrespective of the direction of flow of the liquid and position of the tube in the region of improved heat transfer the wall temperature can drop below the critical temperature of the liquid under study with increasing heat-flux density. This is probably attributable to the fact that the isobaric heat capacity strives toward an extremal value at $t_w \approx t_m$. It could also be associated with the change in the amplitude-frequency characteristics of the process, which, in turn, requires further experimental investigations of convective heat transfer in the region studied.

LITERATURE CITED

1.   G. I. Isaev, Prom. Teplotekhnika, 3, No. 4, 33-37 (1981).
2.   M. A. Kuznetsov, "Thermal properties of normal alkanes in a wide range of values of the state parameters," Candidate's Dissertation in Technical Sciences, Groznyi (1988), p. 214.
3.   É. M. Dubrovina and V. P. Skripov, in: Heat and Mass Transfer [in Russian], Minsk (1965), p. 40.