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DETERIORATION OF HEAT TRANSFER AT SUPERCRITICAL PRESSURES OF A SUBSTANCE

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Results of an experimental investigation of the transition from the enhanced mode of heat transfer to a deteriorated mode at supercritical pressures of toluene are presented.

The great body of experimental data on heat transfer and on the temperature mode of a wall at supercritical pressures of a substance confirm different changes in the wall temperature, which correspond to normal, enhanced, and deteriorated modes of heat transfer [1–6]. Among these, the deteriorated mode is of prime interest from the viewpoint of reliable operation of equipment, since in the occurrence of this mode the temperature increases jumpwise.

The deterioration of heat transfer at supercritical pressures of a substance was observed in experiments with water and carbon dioxide [1–4]. Experiments with hydrocarbons, where the normal and deteriorated modes of heat transfer were noted [5, 6], were conducted mainly on short small-diameter tubes at low temperatures of a liquid at the tube inlet. Results of these experiments can be used in calculations of cooling of a high-temperature surface of equipment; they differ from the data obtained at high temperatures of water as applied to power plants. The development of steam-turbine plants with organic working substances [7, 8] requires a study of the laws governing their heat transfer at supercritical pressures and high temperatures of hydrocarbons. The present work is devoted to this problem.

Toluene (P_{cr} = 4.24 MPa, t_{cr} = 320.7^{o}C), which has found wide application in practice and whose thermophysical properties have been studied rather well, is used as a model liquid [7–9].

The schematic of the experimental setup and the technique of experiments and measurements of individual quantities are given in [10]. The experiments were conducted in the rising motion of toluene in a vertical tube within the following ranges of variation of the operating parameters: P/P_{cr} = 1.06–1.65, t_{liq}^{inl}/t_{cr} = 0.35–0.85, t_{liq}^{outl}/t_{cr} = 0.50–1.40, t_w/t_{cr} = 0.60–1.85, ρu = (60–330) kg/(m^2·sec) q = (0.20–3.50)·10^5 W/m^2, d_{in} = 4/00–6.30 mm, and l_{heat} = 300–12,000 mm.

It is seen from Fig. 1a that for a temperature of the wall lower than the pseudocritical temperature of the liquid (t_{max}), the change in the wall temperature along the tube length corresponds to the normal mode of heat transfer (curve 1). As the heat-flux density increases (at constant values of the operating parameters) the wall temperature increases and approaches the pseudocritical temperature of toluene. Owing to the strong changes in the thermophysical properties of the liquid in the boundary layer for temperatures close to t_{max}, the law governing heat transfer acquires a different character, and the distribution of the wall temperature along the tube length differs from that occurring in the normal mode of heat transfer (curves 2 and 3). It should be noted that the substantial change in the density of the substance in a near-critical state facilitates the origination of free convection in a forced flow. The intensity of heat transfer changes depending on the mutual effects of free and forced flows. An analysis of the data on the heat transfer obtained for the rising

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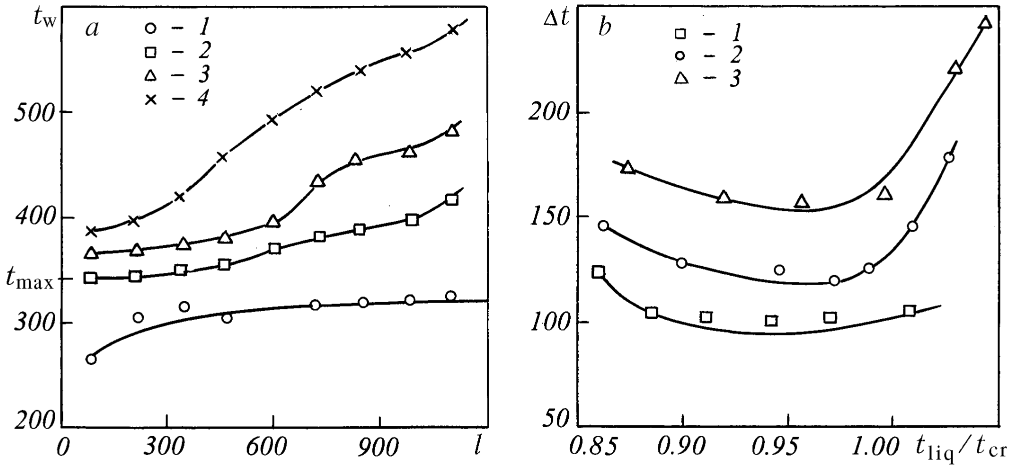

Fig. 1. Wall temperature (a) and the temperature difference (b) as functions of the tube length: a) $q \cdot 10^{-5}$ W/m^2: 1) 0.30; 2) 0.69; 3) 1.78; 4) 2.27; P = 5.0 MPa; l_{heat} = 1200 mm; d_{in}/d_{out} = 6.3/8.0 mm; ρu = 132 kg/(m^2·sec); t_{liq}^{inl} = 244°C; b) $q \cdot 10^{-5}$: 1) 1.03; 2) 1.33; 3) 1.70; P = 4.5; l_{heat} = 300; d_{in}/d_{out} = 6.3/8.0; ρu = 91.9; t_{liq}^{inl} = 265.

motion of toluene in the vertical tube shows that under the effect of free convection heat transfer first is enhanced and then, at certain values of Gr and Re, it deteriorates. We observe the enhancement of heat transfer when $Gr/Re^2 > 0.6$ and deterioration of it when $Gr/Re^2 < 0.6$.

The effect of free convection on the intensity of heat transfer first occurs at the end of the tube and, as the heat flux increases, it shifts to the tube inlet. The deterioration of heat transfer begins also at the tube end and, as the heat flux increases, it moves in the direction opposite to the liquid motion (curves 2–4 in Fig. 1a). At low values of the heat-flux density, the increase in the wall temperature is several tens of degrees and at high values of it the increase is several hundreds of degrees. In these experiments, the normal mode of heat transfer occurs on the initial portion of the tube, while the deteriorated mode occurs on the end portion.

The onset of the increase in the wall temperature that corresponds to the deteriorated mode of heat transfer begins at certain values of the liquid temperature. As the liquid temperature reaches a boundary value ($t_{liq}^{b} = t_{liq}/t_{cr}$ = 0.80–1.00), the wall temperature and accordingly the temperature difference $\Delta t = t_w - t_{liq}$ can increase by tens or even hundreds of degrees (Fig. 1b). The graphs of the dependence $\Delta t = f(t_{liq}/t_{cr})$ show that at small values of the heat-flux density the temperature difference along the tube length changes slightly (curve 1 in Fig. 1b). This regularity is observed in the normal mode of heat transfer. As the heat-flux density increases, the temperature difference on a certain portion of the tube sharply increases (curves 2 and 3 in Fig. 1b). When the mass velocity is $\rho u > 200$ kg/(m^2·sec), the beginning of the deteriorated mode of heat transfer is observed at $t_{liq}^{b} = (0.80\text{–}0.90)t_{cr}$, and when $\rho u < 150$ kg/(m^2·sec), $t_{liq}^{b} = (0.95\text{–}1.00)t_{cr}$.

To reveal the law governing the effect of pressure and mass velocity on heat transfer at supercritical pressures of toluene, experiments were conducted at different values of the pressure and the mass velocity of the heat-transfer agent. The results of these experiments for $t_w > t_{max}$ are presented in Fig. 2a. It is seen from the figure that at a constant value of the specific heat absorption ($q/\rho u \approx$ const) on the initial portion of the tube the wall temperature is approximately the same at different pressures. On the portions of the tube with the deteriorated mode of heat transfer, stratification of the wall temperature is observed at different pressures. It follows from the graphs that the beginning of the increase in the wall temperature corresponds to a flow enthalpy of $h_{liq} \approx 980\text{–}1020$ kJ/kg.

The experimental data obtained for water, carbon dioxide, and toluene show that the deterioration of heat transfer in the rising motion of the liquid in the vertical tube occurs at $h_{liq}^{b}/h_{mass}^{mean} \approx 0.85\text{–}1.00$ (here h_{liq}^{b}

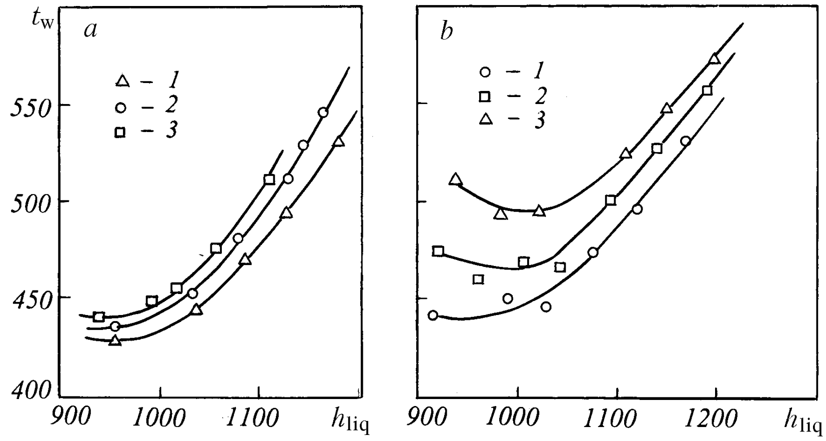

Fig. 2. Wall temperature as a function of the flux enthalpy: (a) 1) P = 4.5 MPa; ρu = 91.9 kg/(m^{2}sec); t_{liq}^{inl} = 265°C; $q/\rho u$ = 1.58 kJ/kg; 2) 5.0, 89.7, 266, and 1.60; 3) 5.5, 94, 270, and 1.64; (b) P = 5.0; 1) ρu = 89.7; t_{liq}^{inl} = 266; $q/\rho u$ = 1.69; 2) 107, 269, and 1.68; 3) 1.26, 264, and 1.63.

and h_{mass}^{mean} are the boundary values of the flow enthalpy corresponding to the beginning of the deteriorated mode of heat transfer and the mean mass enthalpy of the flow at different pressures and at a pseudocritical temperature).

To study the effect of the mass velocity on the change in the wall temperature along the tube length, the experiments were conducted at different velocities. Results of some experiments for $t_w > t_{max}$ and $q/\rho u$ = 1.60–1.67 kJ/kg are given in Fig. 2b. In these experiments, the liquid temperature at the tube inlet has close values. It follows from the graphs of the dependence $t_w = f(h_{liq})$ that for $t_w > t_{max}$ and a low mass velocity, the value of the wall temperature is lower than at high velocities. The increase in the intensity of heat transfer in the case of rising motion at low mass velocities and $t_w > t_{max}$ can be explained by the effect of free convection.

It was noted above that in a number of cases at high temperatures of the liquid and of the heat fluxes the enhanced mode of heat transfer becomes deteriorated. Figure 3 presents the graphs of the change in the heat-transfer coefficient along the tube length $\left(X = \frac{1}{\mathrm{Pe}}\frac{x}{d}\right)$ that correspond to the case of the transition from the enhanced mode of heat transfer to a deteriorated mode.

It is seen from Fig. 3a that for a heat-flux density of $q = 0.63 \cdot 10^5$ W/m^2 in the initial part of the tube on the portion of thermal stabilization the heat-transfer coefficient decreases and then increases, on the tube lengths X = 95–115 it decreases, and in the end part of the tube it changes slightly (curve 1). In these experiments, the normal mode occurs in the initial part of the tube, the enhanced mode occurs in the middle part, and the deteriorated mode of heat transfer occurs in the end part. In the tube cross section, where the transition from the enhanced mode to a deteriorated mode was observed, the relative temperatures of the wall and the liquid had the following values: t_w/t_{cr} = 1.09 and t_{liq}/t_{cr} = 0.89. In this experiment, in the end part of the tube the wall temperature increased from 350 to 375°C.

For a heat-flux density of $q = 0.99 \cdot 10^5$ W/m^2 in the initial part of the tube (to X = 80) the heat-transfer coefficient increases and then decreases (curve 2). In these experiments, heat transfer increases in the initial part of the tube, and above the middle part it deteriorates, i.e., two modes of heat transfer occur.

In our experiment, in the cross section of the tube where the transition from the enhanced to deteriorated heat transfer occurs, the relative temperatures of the wall and the liquid had the following values: t_w/t_{cr} = 1.21 and t_{liq}/t_{cr} = 0.94. Upon the beginning of the deteriorated mode of heat transfer, the wall temperature increased from 388 to 424°C.

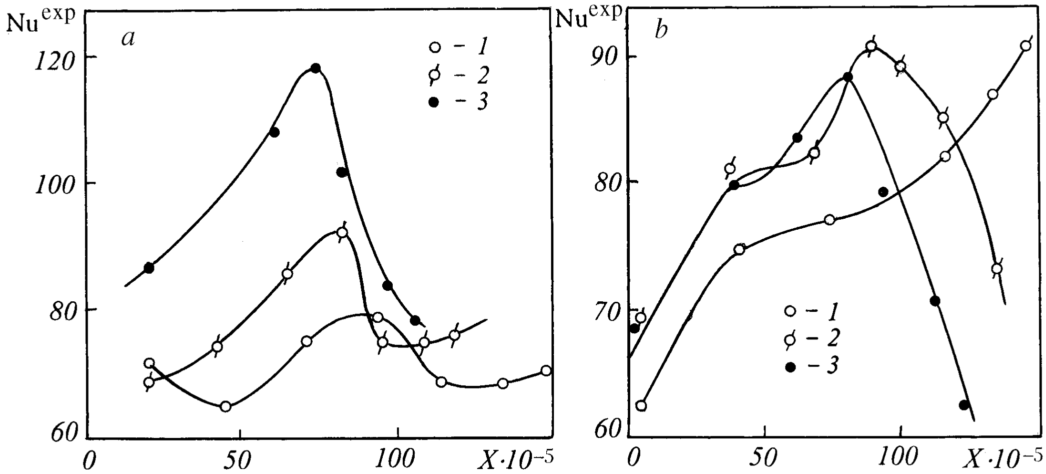

Fig. 3. Change in the Nusselt number along the tube length: (a) $q{\cdot}10^{-5}$ W/m^2: 1) 0.63; 2) 0.99; 3) 1.53; P = 4.5 MPa; ρu = 107 kg/(m^2·sec); $t_{\text{liq}}^{\text{inl}}$ = 269°C; b) $q{\cdot}10^{-5}$: 1) 0.92; 2) 1.20; 3) 1.40; P = 4.5; ρu = 91; $t_{\text{liq}}^{\text{inl}}$ = 265.

For a heat-flux density of $q = 1.58{\cdot}10^5$ W/m^2, the site of transition from enhanced mode of heat transfer to a deteriorated one is noted on lengths X = 70 at the relative temperatures t_w/t_{cr} = 1.32 and t_{liq}/t_{cr} = 0.97. In the end part of the tube, the wall temperature increased from 423 to 530°C. The curves of the dependence Nu = $f(X)$ show that with increase in the heat-flux density (all other things being equal) the length of the tube portion with the deteriorated mode of heat transfer increases.

Similar results are obtained under different conditions (Fig. 3b). In these experiments, for a heat-flux density of $q = 0.92{\cdot}10^5$ W/m^2 under the effect of free convection along the entire length of the tube heat transfer increases (curve 1). Further increase in the heat flux leads to the fact that in the initial part of the tube (to X = 90) the heat-transfer coefficient increases and then decreases (curve 2). In this case, the wall temperature changes from 412 to 415°C, and then, upon the transition from the enhanced mode of heat transfer to a deteriorated mode, i.e., in the end part of the tube, t_w increases from 416 to 463°C. The site of transition of the heat-transfer modes corresponds to a relative temperature of the liquid of t_{liq}/t_{cr} = 0.96. With further increase in the heat-flux density, the general character of change of the heat-transfer coefficient along the tube length is similar to the previous case (curve 3). In this experiment, in the tube cross section where the transition from the enhanced mode of heat transfer to a deteriorated mode occurs, the relative temperature of the liquid is t_{liq}/t_{cr} = 0.97, and the wall temperature in the initial part of the tube increases from 432 to 440°C. In the end part, on the portion with the deteriorated mode of heat transfer the wall temperature increases from 440 to 527°C.

In the deteriorated mode of heat transfer, in a number of cases the wall temperature increases jumpwise. In the deteriorated mode of heat transfer, it is impossible to determine it by ordinary equations of convective heat transfer, since the wall temperature is unknown. The method of successive approximations gives satisfactory results in the case of a monotonic change in the wall temperature along the tube length, which is inapplicable to the deteriorated mode of heat transfer.

CONCLUSIONS

1. The temperature mode of the wall in forced motion of toluene at supercritical pressures has been studied, and the effect of free convection on the intensity of heat transfer has been revealed.

2. The possibility for the deteriorated mode of heat transfer to occur in equipment operating with heated hydrocarbons has been determined.

3. It has been found that with certain combinations of the operating parameters the enhanced mode of heat transfer becomes deteriorated.

NOTATION

P, pressure, MPa; *t*, temperature, °C; *q*, heat-flux density, W/m^2; *d*, tube diameter, mm; *l*, tube length, mm; *x*, distance to the tube inlet, mm; ρ, density of the substance, kg/m^3; ρ*u*, mass velocity, kg/(m^2·sec); *h*, enthalpy, kJ/kg; t_{max}, temperature corresponding to a maximum of the heat capacity at supercritical pressures of the substance, °C; *X*, dimensionless length; Nu, Re, Pr, Gr, and Pe, Nusselt, Reynolds, Prandtl, Grashof, and Péclet numbers. Subscripts: w, wall; liq, liquid; cr, critical; in, inner; out, outer; heat, heated; max, maximum; mass, mass. Superscripts, inl, inlet; outl, outlet; exp, experimental; b, boundary; mean, mean.

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