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HEAT TRANSFER IN A HORIZONTAL COILED PIPE IN A TRANSIENT REGIME AND AT A NEAR-CRITICAL PRESSURE OF A FLUID

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It has been established that in the region of pressures close to a critical one, heat transfer in a transient regime of motion of a single-phase flow in a horizontal coil pipe changes nonuniformly over the cross section of the perimeter. The main factors here are the influence of inertia forces and of free convection. Equations to calculate the heat-transfer coefficient are suggested.

Introduction. Heat exchangers with coil pipes in their construction-technological and operating characteristics considerably excel those with straight pipes applied in various branches of industry. Among their merits one should mention their compactness, a relatively simple compensation of temperature deformation, and a higher heat transfer intensity.

The creation of new apparatuses and cooling of their heating surfaces render basic the problems of contemporary technology. In view of the wider practical application of compact heat exchangers, it has appeared necessary to investigate heat transfer in coil pipes in the region of pressures close to a critical one, which is of great scientific and practical importance. In the present work, we study heat transfer at a subcritical pressure of a fluid which is nearly close to a critical one. Of prime importance are the investigations of heat transfer of the fluids that differ in their physical properties from water. The presence of experimental data with other heat carriers may deepen and expand the current ideas concerning the mechanism of heat exchange with such fluids.

At subcritical pressures, when the physical properties of a heat carrier change insignificantly, the heat transfer intensity in curved pipes depends mainly on the regimes of heat carrier motion and geometrical dimensions of the coil that have been rather well studied.

However, in a near-critical state strong changes in the thermophysical properties of a fluid influence the structure of the flow and heat-transfer intensity. This effect is especially noticeable in the region of heat carrier pressures close to the critical one provided that the wall temperature approaches the saturation one ($t_w \approx t_s \le t_{cr}$) and the fluid temperature is smaller than the latter. In such cases there is a layer near the pipe wall where a sharp change in the thermophysical properties of the fluid occurs; the heat capacity in this layer attains the highest value, whereas the density and viscosity — the lowest ones, and the surface tension and vapor generation heat tend to zero. The variability of the thermophysical properties of the fluid over the cross section and along the flow length in the near-critical region favor a change in the relationship of the forces that realize the fluid motion.

In addition to the above-indicated factors, the heat-transfer intensity experiences the influence of the specific features of the flow in the coil pipe that has concave and convex heat releasing surfaces.

Statement of the Problem. The present work is devoted to investigation of the intensity of heat transfer in a horizontal coil pipe in a transient regime of motion of a single-phase flow and at subcritical pressures of the fluid. As the model fluid we selected toluene (P_{cr} = 4.24 MPa, t_{cr} = 320.8^{o}C). In power engineering it is used in autonomous power plants [1], whereas in the chemical industry it is widely applied to obtain many important technical compounds. The thermophysical properties of toluene have been rather well studied [2], thus providing the possibility of carrying out calculations of thermal processes. Therefore the use of toluene as a model fluid for experimental investigation of the process of heat transfer and of the temperature regime of the wall is justifiable and worthwhile.

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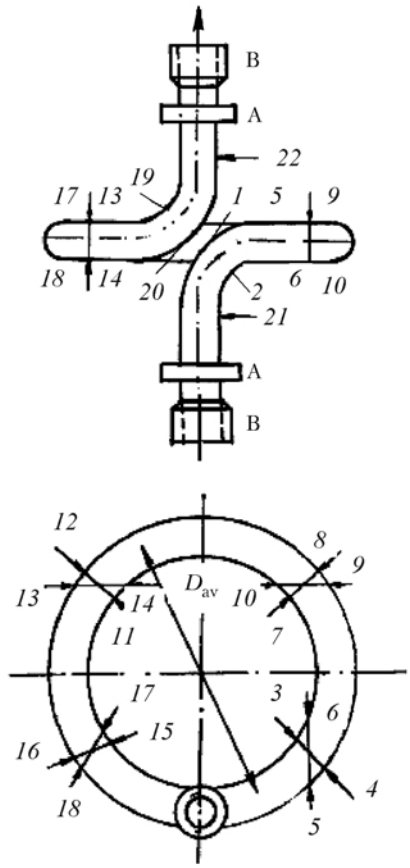

Fig. 1. Schematic diagram of the test section and position of thermocouples: A, current leads; B, mixing chambers; position of thermocouples; 1, 20) on the outer portion of the perimeter bendings, at the inlet and outlet of the coil; 2, 19) on the inner portion of the perimeter, bendings, at the inlet and outlet of the coil; 3, 7, 11, 15, on the internal boundary of the coil perimeter; 4, 8, 12, 16) on the external boundary of the coil perimeter; 5, 9, 13, 18) on the lower boundary of the coil perimeter; 6, 10, 14, 17) on the upper boundary of the tests section perimeter; 21, 22) on the straight portion of the heated section.

Heat transfer was investigated on an experimental setup whose description, experimental procedure, and technique of measuring individual quantities are given in [3]. All of its units are manufactured from 1Kh18N10T stainless steel. Uniform heating of the test section was made by a low-voltage electric current. The temperatures of the fluid and wall were measured by chromel-alumel thermocouples with a wire diameter of 0.2 mm. In each section along the length of the horizontal coil the wall temperature was measured on the lower, upper, and side boundaries of the pipe. Figure 1 presents the schematic diagram of the test section of a horizontal coil and the position of thermocouples. At the inlet and outlet of the coil there are straight vertical portions, in the elbows the direction of the fluid motion changes, and transition from a vertical position to a horizontal and vice versa occurs. In these portions of the coil the heat-transfer intensity also changes.

Experiments were carried out at constant operating conditions, but at a constantly increasing heat flux. In each test the heat balance was checked, i.e., a comparison was made between the heat flux calculated from the electric power and that absorbed by the fluid. The difference between them did not exceed 3%. The error in the calculation of the heat flux from the electric power value was estimated to be 1.8%.

In the tests the operating conditions varied in the following limits: P/P_{cr} = 0.35–0.95, ρu = 150–550 kg/(m^2·sec), $\Delta t/t_{cr}$ = 0.2–0.8, d_{in}/d_{out} = 4/6 mm, D_{av} = 115 mm, l_h = 525 mm, $q = (0.79\text{–}1.9)\cdot 10^5$ W/m^2.

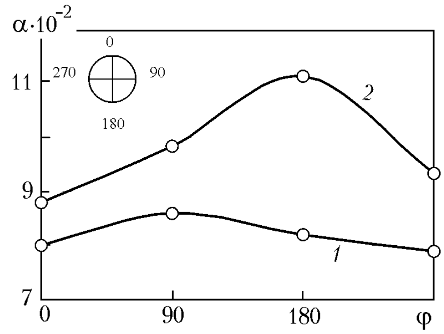

Fig. 2. Change in the heat transfer coefficient α around the perimeter of the cross section at P = 4.0 MPa, ρu = 287.5 kg/(m^2·sec); q = 1.25·10^5 W/m^2 (1) and 1.75·10^5 (2). α, W/(m^2·deg); φ, deg.

Experimental data on heat transfer at subcritical pressures of heat carrier characterize the nonuniformity in the wall temperature distribution around the perimeter and along the length of the heated horizontal coil pipe. The reasons for this are the appearance of inertia forces, the influence of free convection, strong and peculiar changes in the physical properties of the heat carrier at near-critical pressures, etc. Naturally, these factors influence the hydrodynamics of the flow as well as the heat-transfer intensity. As a result, in a single-phase flow at subcritical pressures of the substance the heat-transfer intensity changes.

In addition to the above-indicated factors, the character of the fluid flow in a curvilinear channel is influenced by the shape and dimensions of the channel cross section and the radius of its bending. The turning of a flow in a curvilinear channel leads to the appearance of an inertia centrifugal force acting across the flow which in turn changes the conditions of fluid motion and its heat exchange with the wall. Under the action of centrifugal forces the boundary layer thickness on the concave side that corresponds to the outer boundary of the horizontal coil pipe decreases, whereas on the opposite convex side (internal boundary) it increases. The thicker the boundary layer and the lower the thermal conductivity of the heat carrier, the smaller the heat-transfer rate.

In the process of fluid heating in coils the inner surface of the coil is heated differently over the perimeter. Under usual conditions, in the curvilinear part of a horizontal coil the fluid flow has a complex character. Under the action of centrifugal forces the fluid flows well past the surface of the outer lateral side (90°) of the pipe, at the same time on the opposite inner lateral side (270°) there is a boundary layer with a high thermal resistance. The upper (0°) and lower (180°) boundaries of the perimeter are between these regions (Fig. 2). Under certain conditions, i.e., at a near-critical pressure and in the case of a great difference between the temperatures of the wall and fluid, free convection sets in, the convective currents of which are directed from below upward, and the lower part of the pipe section (180°) is well immersed in the fluid flow. At the same time, the upper part of the section (0°) is filled by heated amounts of the fluid, and this decreases the exposure of the surface to the fluid flow and, as a result, the heat-transfer intensity decreases. As the heat flux increases, the difference between the coefficients of heat transfer from the upper, lower, and also from the side boundaries of the pipe becomes greater (curve 1, Fig. 2). However, with further increase in q, the difference between the side boundaries becomes nearly stabilized, and it increases between the upper and lower ones (curve 2, Fig. 2). This indicates an increase in the influence of free convection on the wall temperature distribution over the cross section of the perimeter. Thus, at low heat fluxes (correspondingly at small values of the temperature difference between the wall and fluid) heat transfer on the outer side boundary was the highest value and on the inner side boundary it has the lowest value, with the heat transfer from the upper and lower boundaries lying in between them. As q increases, the heat transfer from the lower boundary increases under the influence of free convection and may exceed the values from the external side boundary.

The influence of the above-indicated factors on the heat-transfer intensity is manifested differently in a laminar mode of flow ($\mathrm{Re}_{\mathrm{fl}.d} < 2300$), transient ($2300 < \mathrm{Re}_{\mathrm{fl}.d} < 10^4$), and turbulent ($\mathrm{Re}_{\mathrm{fl}.d} > 10^4$) modes of flow.

Discussion of Results. Below we will restrict ourselves to the generalization of experimental data on heat transfer in a transient mode of a single-phase flow at a near-critical pressure. As has been noted, in horizontal coils

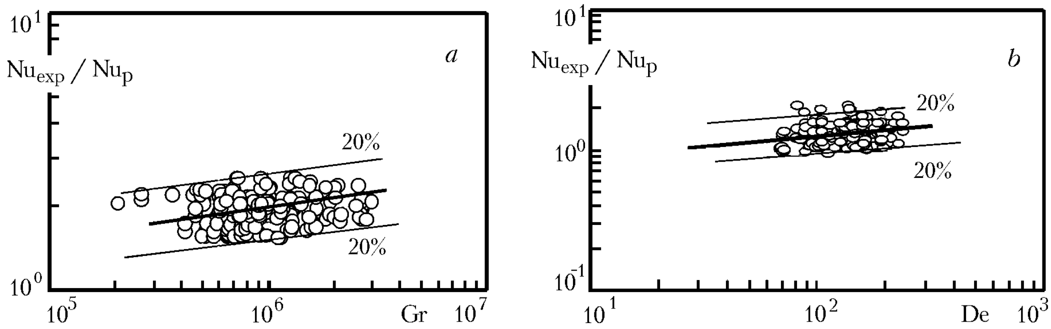

Fig. 3. Nu_{exp}/Nu_p vs. the Grashof number (a) and Dean number (b).

mainly free convection exerts its influence on heat transfer at the upper and lower boundaries and an inertial force on the side boundaries.

Figure 3 presents a comparison of calculated and experimental values of the Nu number, where the predicted values of Nu_p in a transient regime of motion were found from the equation [4]

$$Nu_p = A\varepsilon\, Re_{fl}^{0.7} Pr_{fl}^{0.43} \left(\frac{\mu_{fl}}{\mu_w}\right)^{0.2} .$$

According to Fig. 3a, the data obtained for the upper and lower boundaries of the horizontal coil with a single-phase flow deviate from the averaging line approximately by 20% depending on the influence of free convection. The points above the averaging line correspond to the data obtained for the lower boundaries and those under it — for the upper boundaries of the tube. The following equation was suggested to describe the averaging line:

$$Nu_{fl} = A\varepsilon\, Re_{fl}^{0.7} Pr_{fl}^{0.43} Gr_{fl}^{0.18} \left(\frac{\mu_{fl}}{\mu_w}\right)^{0.2} , \tag{1}$$

where A = 0.0037 and $\varepsilon = 1 + 3.54\dfrac{d_{in}}{D_{av}}$. By increasing the constant quantity A by about 15%, it is possible to determine the heat transfer coefficient for the lower boundaries of the horizontal coil at a near-critical pressure and in a transient regime of single-phase fluid motion. Correspondingly, α for the upper boundaries of the coil can be found on having decreased A by 15%.

The heat transfer intensity on the side boundaries of the horizontal coil depends in the main on the mode of fluid flow, inertial forces, geometrical dimensions, and on the diameter of the coil bending. However, at a near-critical pressure, when the thermophysical properties of the fluid change sharply and free convection is substantially intensified, there occurs equalization of heat transfer from the external and side boundaries. This can be attributed to the fact that the inertial force is equal to the product (taken with a reverse sign) of the fluid density by the acceleration of its considered element [5]. With decrease in the fluid density, the influence of free convection increases, whereas the influence of inertial forces on the heat transfer from the side boundaries of the coil becomes stabilized.

It has been noted above that the inertial forces mainly exert their influence on the heat transfer intensity on the side boundaries of the coil. The heat transfer data obtained for these boundaries are generalized by the dimensionless equation

$$Nu_{fl} = 0.025 Re_{fl}^{0.7} Pr_{fl}^{0.43} De_{fl}^{0.15} \left(\frac{\mu_{fl}}{\mu_w}\right)^{0.2} . \tag{2}$$

In the generalizing equation (2) the Dean number (De_{fl} = $Re\sqrt{d/D}$ [6] takes into account the influence of inertial forces, in view of which there is no need to use the tube bending curvature factor ε. This equation is valid for both external and internal side boundaries at a near-critical pressure of a single-phase fluid and high Gr numbers (Fig. 3b).

CONCLUSIONS

1. New data on heat transfer in a transient single-phase regime of motion of toluene at subcritical, but close to critical, pressures in a horizontal coil are obtained.

2. It is noted that in the region of pressures close to the critical one the heat transfer from the upper, lower, and side external–internal boundaries of a horizontal coil has different values.

3. Dimensionless equations to calculate heat transfer from the upper–lower and side boundaries of the coil are suggested.

NOTATION

d, tube diameter, mm; D_{av}, average diameter of the coil, mm; De, Dean number; Gr, Grashof number; l, tube length, mm; Nu, Nusselt number; P, pressure, MPa; Pr, Prandtl number; q, heat flux density, W/m^2; Re, Reynolds number; t, temperature, ^oC; t_s, saturation temperature, ^oC; u, velocity, m/sec; α, heat transfer coefficient, W/(m^2·deg); μ, dynamic viscosity, Pa·sec; ρ, fluid density, kg/m^3; ρu, mass velocity, kg/(m^2·sec); φ, angle of the position of thermocouples around the tube circumference. Subscripts: av, average; cr, critical; exp, experimental; h, heated; fl, fluid; in, inner; out, outer; p, predicted; s, saturation; w, wall.

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