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HEAT TRANSFER TO AN ASCENDING LAMINAR FLOW OF HYDROCARBONS UNDER SUPERCRITICAL PRESSURE CONDITIONS

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Some results of experimental investigations of heat transfer of n-heptane in a laminar forced flow under the conditions of supercritical pressures are presented, and equations to estimate the intensity of heat transfer under viscous and viscous-gravitational conditions are suggested.

The increase in the intensity of heat transfer is the principal problem in creating small-size, efficient heat-exchanging systems. The current stage in the development of science in the field of convective heat transfer allows us to consider that passage of substances to supercritical pressures may be one of the main conditions which could ensure efficient operation of apparatuses and, on the whole, meet the above-specified problem. Under the conditions considered, of importance is the problem of reliable operation of heat-exchanging apparatuses and units. To study the very complex processes that occur in them and that are associated with both the appearance of additional effects in the system which cause thermoacoustic fluctuations of the fluid pressure with different frequencies and with the temperature of the cooled channel-wall surface, it is necessary to carry out special investigations, in particular, of various regimes of forced heat-carrier flows.

In the region of supercritical pressures, by now a great number of experimental works have been conducted with the use of various heat carriers; all of the works relate mainly to a turbulent mode of forced flow. However, their results are still insufficient for complete understanding of the physical essence of the mechanism of heat transfer at variable physical properties of the medium and, consequently, for obtaining equations to estimate the intensity of heat transfer.

It was thus needed to expand the region of investigations and thereby deepen the current knowledge and notions of the reason for the appearance of individual patterns of convective heat transfer under the conditions of supercritical pressures of heat carriers and the nature of this phenomenon.

In connection with the foregoing, in the present work we give some of the results of experimental investigation of heat transfer to an ascending laminar flow of *n*-heptane under the conditions of supercritical pressures (P_{cr} = 2.736 MPa, T_{cr} = 540.16 K).

The main advantages of organic heat carriers are that, first, they possess a relatively low value of critical pressure and do not cause corrosion of structural materials and, second, the possibilities of implementing single-circuit schemes with organic substances in atomic power engineering have been repeatedly considered in the literature, and the ideas of using various hydrocarbons in a reactor have been put forward. Moreover, the thermophysical properties of *n*-heptane have been investigated in detail in wide ranges of pressures and temperatures. The availability of data on the thermophysical properties of substances is required in order to analyze and correlate the results obtained.

Heat transfer was investigated on an experimental setup which is an open circulation loop made of stainless steel. A detailed description of the setup and experimental procedure are given in [1]. The basic element of the setup is an experimental tube made of 12X18H10T and 0X18H10T stainless steel the length and diameter of which were selected in conformity with the investigations carried out. The working section was thermally and hydrodynamically stabilized. The experimental tubes were heated by a variable low-voltage electric current, and the current strength was regulated by means of single-phase and step-down transformers.

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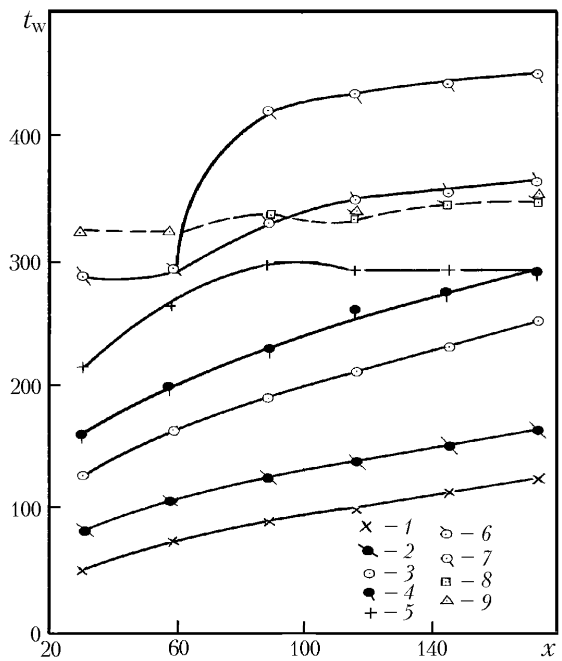

Fig. 1. Dependence $t_w = f(x)$: 1) $q = 0.298 \cdot 10^5$ W/m^2; 2) $0.4120 \cdot 10^5$; 3) $0.664 \cdot 10^5$; 4) $0.809 \cdot 10^5$; 5) $1.118 \cdot 10^5$; 6) $1.638 \cdot 10^5$; 7) $2.173 \cdot 10^5$; 8) $2.189 \cdot 10^5$; 9) $3.938 \cdot 10^5$.

In determining the heat-transfer coefficient in the course of investigations, the maximum possible relative error was equal to 19% and the mean-square one to 14%. The operating conditions of the process were: $P = (1.09–3.00)P_{cr}$; $t_{fl} = (0.03–1.04)t_{cr}$, $t_w = (0.11–2.62)t_{cr}$, $Re_{fl,d} = 500–3200$, $Gr_{fl,d} = 10^4–10^6$, and $q = 10^4–2 \cdot 10^6$ W/m^2.

For thermal calculations and reliable estimation of the temperature conditions of the cooled tube-wall surface in highly efficient heat-exchanging apparatuses, it is very important to know the laws governing the wall-temperature distribution along the tubes. Therefore, first we consider the distribution of the temperature of the cooled surface of the wall along the vertical tube. The curves presented in Fig. 1 were plotted using the results of investigations carried out with an ascending flow of *n*-heptane under conditions with $P = 4.0$ MPa, $t_{fl}^{in} = 10^oC$, and $\rho W = 250$ kg/(m^2·sec). It is seen from the figure that at a wall temperature lower than the pseudocritical temperature of the agent investigated, the character of the distribution of the cooled surface of the tube wall is the same as in the case of conventional convective heat transfer under subcritical pressures (curves 1–4). With an increase in the heat-flux density, the temperature of the cooled surface of the tube wall, while increasing, approaches the pseudocritical temperature of the fluid investigated and, as a result of a strong and specific change in the thermophysical parameters (especially in C_p and ρ), some deteriorations in the monotonicity in the wall-temperature distribution along the tube are observed in the wall layer. In its final part, a certain decrease in the temperature of the cooled surface is observed, which points to the onset of an improved regime of heat transfer (curve 5). Typical of such regimes is that with a subsequent increase in the heat-flux density, the local temperature of the cooled tube-wall surface remains practically intact, and the experimental points obtained at different values of heat fluxes merge. In the case considered, the mentioned regime of heat transfer covers the range of change in the heat-flux density from $1.11 \cdot 10^5$ to $1.61 \cdot 10^5$ W/m^2. It should be noted, however, that the range of the heat-flux density covered by the heat-transfer regime indicated will depend, in our opinion, on the magnitude of the mass velocity of the flow moving in the channel. A comparison of the results of earlier [1–5] and present investigations shows that a decrease in the mass velocity of a moving flow leads to a noticeable decrease in the heat-transfer intensity in the region with $t_w \approx t_m$.

The results of investigations show that in the range of heat-flux densities from $1.63 \cdot 10^5$ to $2.17 \cdot 10^5$ W/m^2 in sections with $x > 60$ mm from the tube inlet, the wall-surface temperature increases (curves 6 and 7), followed by a relatively deteriorated heat-transfer regime. In sections with $x < 60$ mm, the values of the temperature of the cooled tube-wall surface at different heat-flux densities differ slightly as before and, consequently, over this section the proc-

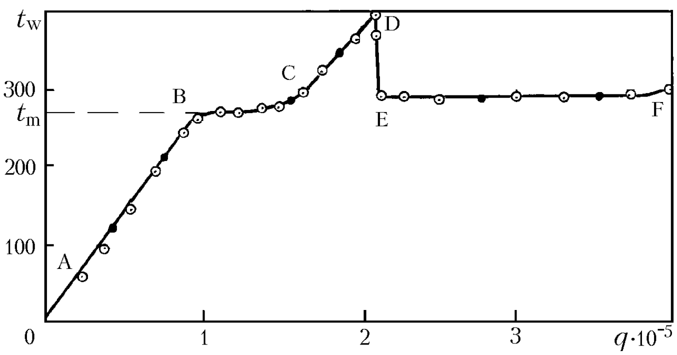

Fig. 2. The character of a change in t_w depending on q.

TABLE 1. Experimental Values of t_{fl}, α, and Re

No. of the run	t_{fl}	α	Re	No. of the run	t_{fl}	α	Re
1	12.5	338	1087	12	45.4	593	1534
2	15.6	331	1124	13	50.1	593	1587
3	20.3	342	1182	14	52.0	597	1618
4	23.0	338	1205	15	53.3	660	1645
5	27.5	373	1282	16	54.8	865	1667
6	29.2	407	1302	17	57.8	969	1736
7	32.1	456	1323	18	62.1	1089	1773
8	34.5	512	1366	19	73.1	1373	1961
9	38.2	571	1425	20	80.2	1556	2083
10	42.1	601	1479	21	88.3	1801	2242
11	43.5	596	1502	22	94.4	1948	2347

ess of heat transfer is enhanced. At high values of the heat-flux density and at a high temperature of the tube-wall surface that releases heat, a decrease in the temperature of the wall over the entire length to the value $t_w = t_m + 20^oC$ was detected (curves 8 and 9). In the range of heat-flux densities from $2.17 \cdot 10^5$ to $3.98 \cdot 10^5$ W/m^2, the temperature of the cooled wall surface in some of the tube sections has approximately the same value, which characterizes a stable regime of improved heat transfer.

Thus, in the range of the heat-flux densities from $0.16 \cdot 10^5$ to $3.98 \cdot 10^5$ W/m^2, the following regimes of heat transfer have been revealed (Fig. 2): a normal one (portion AB, $q = 0.16 \cdot 10^5$–$1.00 \cdot 10^5$), an improved one (portion BC, $q = 1.00 \cdot 10^5$–$1.61 \cdot 10^5$), a relatively deteriorated one (portion CD, $q = 1.61 \cdot 10^5$–$2.17 \cdot 10^5$), and a stable regime (portion DEF, $q = 2.17 \cdot 10^5$–$3.98 \cdot 10^5$). Among the regimes enumerated, the stable regime of improved heat transfer covers a rather wide range of heat-flux densities. This is well seen from the $t_w = f(q)$ plot constructed from the readings of the thermocouples located at a distance of x = 110 mm from the tube inlet and from the results of investigations carried out at P = 3.0 MPa, $t_{fl}^{in} = 10^oC$, and ρW = 250 kg/(m^2·sec). The results of measurements of the inverse sequence (measurements with a decreasing heat-flux density) are shown by filled points in the figure.

Table 1 contains experimental values of the surrounding medium temperature and heat-transfer coefficient, as well as of the Reynolds number for the tube section considered. It is seen that the Reynolds number changes within the limits 1087–2347, i.e., the fluid flow regime in the channel is laminar.

As noted above, the heat output by *n*-heptane was investigated by us under conditions where the thermophysical properties of the fluid investigated undergo strong and peculiar changes that influence the course of the process and intensity of heat transfer. This fact and other additional factors typical of the region investigated make the mechanism of heat transfer still more complex and, in this connection, the development of computational recommendations for estimating the intensity of convective heat transfer is rather difficult. It should be emphasized that the foregoing is typical not only of a laminar regime but also of other regimes of forced and free motions of a fluid.

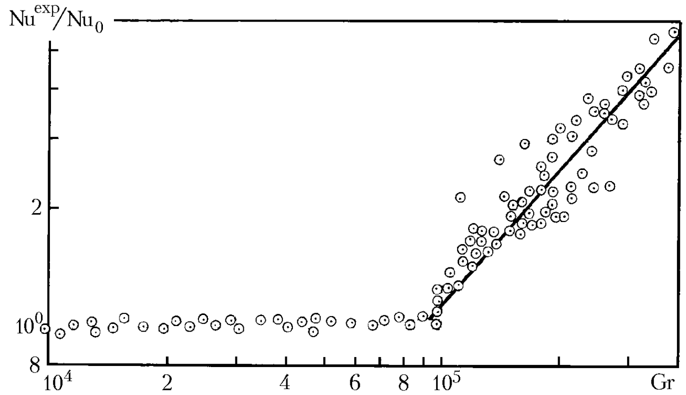

Fig. 3. The dependence $\frac{Nu^{exp}}{Nu_0} = f(Gr)$.

Despite the difficulties mentioned, in the present work we make an attempt to generalize the experimental data on heat transfer obtained under the conditions of a supercritical pressure of *n*-heptane in a laminar regime of forced fluid motion in a vertical tube from below upwards, i.e., in the case of coinciding forced and natural motions. Figure 3 presents the dependence $\frac{Nu^{exp}}{Nu_0} = f(Gr)$, where Nu^{exp} is the experimental value and Nu_0 is the calculated value of the Nusselt number for an isothermal flow, both determined from the well-known formula [6]

$$Nu_{0fl,x} = 0.33 Re_{fl,x}^{0.50} Pr_{fl,x}^{0.43} \left(\frac{Pr_{fl,x}}{Pr_{w,x}}\right)^{0.25} \left(\frac{x}{d}\right)^{0.10} . \quad (1)$$

Here, the distance of the section considered from the beginning of the tube is adopted as the determining dimension, whereas the fluid temperature mean in the given section is taken as the determining temperature (the value $Pr_{w(x)}$ is selected on the basis of the local temperature of the wall) [6]. Equation (1) can be written in the form

$$Nu_{0fl,d} = 0.33 Re_{fl,d}^{0.50} Pr_{fl,x}^{0.43} \left(\frac{Pr_{fl,x}}{Pr_{w,x}}\right)^{0.25} \left(\frac{d}{x}\right)^{0.40} . \quad (2)$$

As is seen from the figure, the plot indicated can be divided into two parts: $Gr < 10^5$ and $Gr > 10^5$. When $Gr < 10^5$, the influence of free convection on the character of change in heat transfer is not felt, and the local values of the heat-transfer coefficient can be determined from Eq. (2). When $Gr > 10^5$, experimental data on the local value of the heat-transfer coefficient are described by the dimensionless equation

$$Nu_{fl,d} = 0.368 Re_{fl,d}^{0.50} Pr_{fl,x}^{0.43} \left(Gr \cdot 10^{-5}\right)_{fl,d}^{1.20} \left(\frac{d}{x}\right)^{0.40} \quad (3)$$

or, subject to Eq. (2), Eq. (3) can be presented in the form

$$Nu_{fl,d} = 1.115 Nu_{0fl,d} \left(Gr \cdot 10^{-5}\right)_{fl,d}^{1.20} , \quad (4)$$

where, according to [7],

$$Gr = g\,(\rho_{fl} - \rho_w)\,\rho_{fl} \frac{d^3}{\mu_{fl}^2} . \quad (5)$$

Dimensionless relations (2) and (4) describe the heat transfer of *n*-heptane under viscous and viscogravitational conditions, respectively, within the error of experiment.

NOTATION

C_p, isobaric heat capacity, kJ/(kg·K); d, inner diameter of the tube, mm; Gr, Grashof number; g, free-fall acceleration, m/sec^2; Nu, Nusselt number; P, pressure, MPa; Pr, Prandtl number; P_{cr}, critical pressure, MPa; q, heat-flux density, W/m^2; Re, Reynolds number; t_{fl}, fluid temperature, ^oC; T_{cr} and t_{cr}, critical temperatures, K, ^oC; t_{fl}^{in}, fluid temperature at the inlet, ^oC; t_w, temperature of the inner wall surface, ^oC; t_m, pseudocritical temperature, ^oC; W, average velocity of the fluid, m/sec; x, distance from the tube inlet, mm; α, heat-transfer coefficient, W/(m^2·^{o}C); μ, dynamic coefficient of viscosity, N·sec/m^2; ρ, density, kg/m^3. Subscripts: fl, fluid; cr, critical; 0, isothermal flow; w, wall; m, pseudocritical. Superscripts: exp, experiment; in, inlet.

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