Journal of Engineering Physics and Thermophysics, Vol. 75, No. 5, 2002

EXPERIMENTAL INVESTIGATION OF CHANGES IN THE WALL TEMPERATURE IN DIFFERENT REGIMES OF MOTION OF SUPERCRITICAL-PRESSURE LIQUIDS

R. F. Kelbaliev

UDC 536.24.08

Results of an investigation of the temperature regime of a wall for the laminar, transient, and turbulent regimes of motion of an ascending flow and different temperatures of toluene are given. Conditions for the occurrence of improved and impaired regimes of heat transfer with different characters of changes in the wall temperature are revealed.

One efficient means of increasing the capacity and improving the economical operation of power plants is the employment of a supercritical-pressure working medium or heat-transfer agent in them. Therefore, substances at supercritical pressures have found wide application in various branches of modern technology, in particular, in power engineering, rocket engineering, the gas industry, cryogenics, and other fields.

In power engineering, one uses water as the working medium and helium as the cooling agent in superconducting magnetic systems and cryogenerators. Hydrocarbons are used in the cooling systems of aircraft and power plants. There are other fields of technology in which different heat-transfer agents at supercritical pressures are widely used.

A characteristic feature of the near-critical state is the substantial change in the thermophysical properties of a substance in the indicated region, which influences the hydrodynamics of the flow. Individual effects lead to a change in the flow structure, which finally influences the intensity of heat exchange. As a result, the heat transfer is improved or impaired as compared to the normal conditions of heat exchange.

In designing and using heat-engineering plants, one must know the temperature regimes of the walls of heat-exchange apparatuses. Therefore, it becomes necessary to study the regularities of their change and to create substantiated methods of calculation of local heat-transfer coefficients.

A great body of experimental data on heat transfer and the temperature regime of the wall obtained for the laminar, transient, and turbulent regimes of motion of the liquid exists in the literature. Here, water [1–3], hydrocarbons [4–8], carbon dioxide, helium, and other substances [9, 10] have been used as the heat-transfer agent or the working medium. However the heat transfer was mainly investigated in the turbulent regime of liquid motion. Data for the laminar and transient regimes of motion are comparatively scarce [5, 6]. At the same time, such regimes of motion are frequent in heat-exchange apparatuses operating with hydrocarbons.

Substances used in various branches of technology differ in thermophysical properties and changes in them. Furthermore, depending on the process occurring in the apparatus, the temperature of the supercritical-pressure liquid can be lower or higher than the critical one. In cooling the high-temperature surface, the substance arrives at the apparatus at low temperatures and leaves it in the liquid state; when $t_w \geq t_m$ its thermophysical properties substantially change over the cross section of the flow. At thermal power stations, water is heated before its arrival at the steam generator and changes to steam in steam-generator tubes (phase transition of the second kind). In such apparatuses, strong changes in the thermophysical properties of the liquid occur both along the radius and length of the tube.

In the first case, as the heat flux increases the region of strong change of the thermophysical properties of the substance (its near-critical state) moves, along the radius, from the wall toward the tube axis under constant operating conditions. The site of location of this region depends on the liquid temperature. Thus, part of the flow experiences

---

Azerbaijan State Petroleum Academy, Baku, Azerbaijan. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 75, No. 5, pp. 25–29, September–October, 2002. Original article submitted February 20, 2001; revision submitted February 27, 2002.

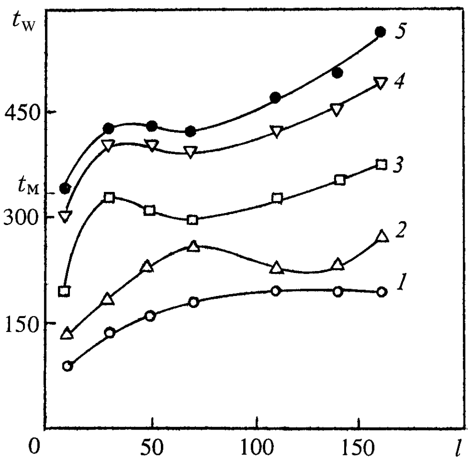

Fig. 1. Change in the wall temperature along the tube length at $P = 4.5$ MPa, $t_{\rm liq}^{\rm out} = 15^{\rm o}{\rm C}$, $\rho u = 90$ kg/(m^2·sec), $d_{\rm outs}/d_{\rm ins} = 4.00/3.02$ mm, and $q\cdot 10^5$ W/m^2: 1) 0.30; 2) 0.68; 3) 1.44; 4) 2.10; 5) 2.34.

the critical state along the tube radius. In the second case, a strong change in the thermophysical properties can also occur along the tube length. The entire flow experiences the critical state.

Experimental data on the temperature regime obtained with hydrocarbons in turbulent motion and corresponding to the first case prove the presence of the normal and improved regimes of heat transfer [4–7] while the data obtained for water and corresponding to the second case demonstrate the presence of the normal and impaired regimes of heat transfer [1–3].

To elucidate the regularity of the heat transfer of a substance at supercritical pressures it is expedient to experimentally investigate the temperature regime of the wall with one liquid for different temperatures and regimes of motion. We selected toluene with well-studied thermophysical properties as the model liquid.

The temperature regime of the wall is investigated in the stationary thermal regime on an experimental setup operating on the principle of an open circulation loop. The circulation and pressure of the liquid in the loop are produced by a pump. A low-voltage electric current is used to heat the experimental tube and preheat the liquid. During the experiments, we measure the temperatures of the liquid and the wall, the flow rate and pressure of the liquid, and the voltage and strength of the current. All the quantities are measured by the known methods. The experiments are conducted in the following order. Electric heating of the experimental tube is switched on for constant values of the flow rate, temperature, and pressure of the liquid at the inlet to the tube. The heat load is held constant for each experiment. The heat flux is gradually increased in passing from one experiment to another.

Changes in the wall temperature are investigated experimentally in different regions of motion for the ascending flow in a vertical tube in the following ranges of variation of the parameters: $P/P_{\rm cr} = 1.06–3.05$; $t_{\rm liq}^{\rm in}/t_{\rm cr} = 0.05–0.85$, $t_{\rm liq}^{\rm out}/t_{\rm cr} = 0.50–1.40$, $t_{\rm w}/t_{\rm cr} = 0.20–1.85$, $q = (0.01–6.00)\cdot 10^6$ W/m^2, $\rho u = 40–3200$ kg/(m^2·sec), ${\rm Re}_{\rm in} = 400–10{,}000$, ${\rm Re}_{\rm out} = (8–60)\cdot 10^3$, $d_{\rm ins} = 2.00–6.30$ mm, and $l_{\rm heat} = 200–1200$ mm.

From the plots of Fig. 1 it follows that for the laminar regime of motion and low temperatures of the liquid the change in the wall temperature along the tube length corresponds to the normal regime of heat transfer (curve 1). It should be noted that ${\rm Re}_{\rm out} = 400$ in these experiments; the liquid is heated as it moves along the tube length and the value of Re increases. The highest value ${\rm Re}_{\rm liq.d} = 4600$ along the tube length was obtained for $q = 2.34\cdot 10^5$ W/m^2 (curve 5). The data on the temperature regime of the wall correspond to the laminar and transient regimes of motion of toluene at low temperatures ($t_{\rm liq}^{\rm in} = 15^{\rm o}{\rm C}$). In these experiments, the wall temperature increases throughout the length of the tube with increase in the heat flux (for constant values of the pressure, temperature, and flow rate of the liquid). However, when $t_{\rm w} > 200^{\rm o}{\rm C}$, the curve of the dependence $t_{\rm w} = f(l)$ develops a wavy character. For example, at the beginning of the tube $t_{\rm w}$ increases on the portion of thermal stabilization, then it decreases by several degrees and increases again on the final portion (curves 2 and 3). In these experiments, the values of the Re numbers along the tube length are no higher than Re = 2200 and the change in the wall temperature corresponds to the laminar regime of motion. The wavy character of the change in the wall temperature on the plot of $t_{\rm w}$ as a function of l is attributable to

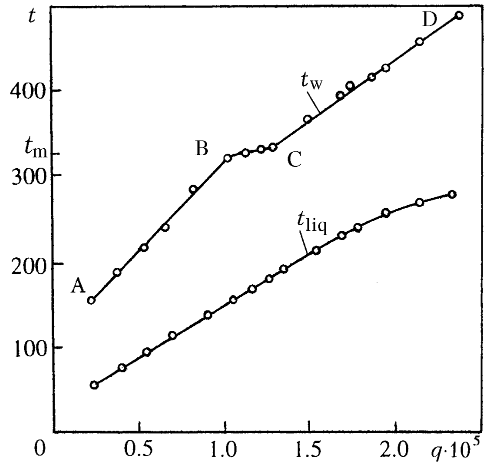

Fig. 2. Temperatures of the wall and the liquid vs. heat-flux density at P = 4.5 MPa, t_{liq}^{in} = 15°C, ρu = 90 kg/(m^2·sec), and d_{outs}/d_{ins} = 4.00/3.02 mm.

the influence of free convection on the intensity of heat transfer, which is pronounced above the central part of the tube and moves in the direction opposite to liquid motion with increase in the heat flux.

When the values of the heat flux are high, t_w increases in the initial part of the tube, changes insignificantly further along the length on a certain segment of it, and increases above the central part of the tube (curves 4 and 5); liquid flow changes from the laminar regime to a transient one along the tube length. In certain experiments, when t_w = 350–400°C, the wall temperature decreases in the initial part of the tube and increases in the final part.

It has been established by experimental investigations of the heat transfer of supercritical-pressure toluene at low temperatures that the onset of the nonmonotone change in the wall temperature occurs at $t_w < t_m$ in the laminar regime of motion, at $t_w \leq t_m$ in the transient regime, and at $t_w \approx t_m$ in the turbulent regime of motion. In the ascending flow, the increase in the temperature at $t_w >$ 400°C is observed in the final part of the tube in the case of laminar motion and in the central part of the tube in the case of turbulent flow. Furthermore, for the laminar flow and $t_w >$ 400°C the wall temperature increases from the beginning to the end of the tube; for the transient regime of motion t_w increases in the initial part of the tube, decreases in the central part, and increases again in the final part. In turbulent flow, t_w increases from the beginning to the center of the tube and decreases in its final part. In all the regimes of motion at $t_w \approx t_m$ the wall temperature changes slightly and the heat transfer is intensified with increase in the heat flux.

Figure 1 shows the general character of change in the wall temperature along the tube length for different heat fluxes, while Fig. 2 gives, for the same experiments, changes in the wall and liquid temperature for the cross section located at a distance of x/d = 47 from the inlet of the tube. From the plot of t_w as a function of q it follows that the change in the wall temperature at $t_w < t_m$ is also the same in the normal regime of heat transfer (portion AB). When $t_w \approx t_m$ the temperature curve changes and a mildly sloping portion BC in which the heat transfer becomes improved is formed. The formation of portion BC on the plot of t_w as a function of q is attributed to the influence of free convection and to the strong changes in the thermophysical properties of toluene on heat transfer at a nearly t_m temperature. When $t_w = t_m$ the liquid in the wall layers is in the near-critical state; its heat capacity increases and its density decreases. Accordingly the cooling power of the liquid increases and free convection occurs. Furthermore, the density change contributes to the acceleration of the flow. As the heat flux increases further, the portion CD of the plot is formed in which $t_w > t_m$. Under these conditions, the region of strong change of the thermophysical properties moves over the cross section of the flow from the wall toward the tube axis.

We note that the increase in the wall temperature in the final part of the tube (curves 4 and 5 in Fig. 1) should not be assigned to the impairment of heat transfer. The portion CD of the dependence $t_w = f(q)$ corresponds, in these experiments, to the final part of the tube (x/d = 47). From Fig. 2 it is clear that the slope of portion CD is somewhat lower than the slope of portion AB where the regime of heat transfer is normal. In other words, if the behavior of the temperature curve of portion AB on the plot of the dependence $t_w = f(q)$ is conventionally extended to higher values of the heat flux, the wall temperature on this curve will be several degrees higher than on portion CD.

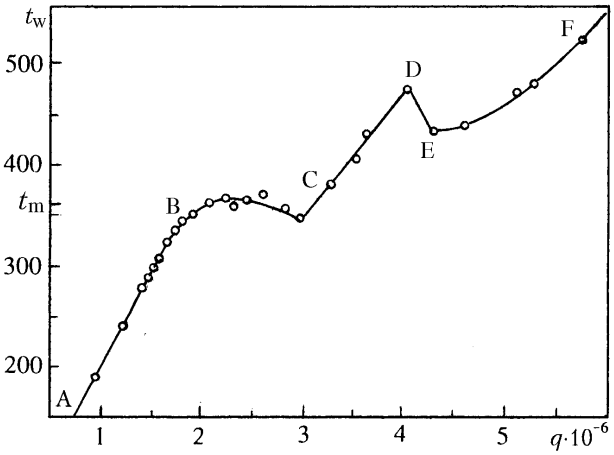

Fig. 3. Wall temperature vs. heat-flux density in the turbulent regime of motion of toluene at P = 6.5 MPa, $t_{\text{liq}}^{\text{in}}$ = 20°C, ρu = 3000 kg/(m^2·sec), and $d_{\text{outs}}/d_{\text{ins}}$ = 3.10/1.91 mm.

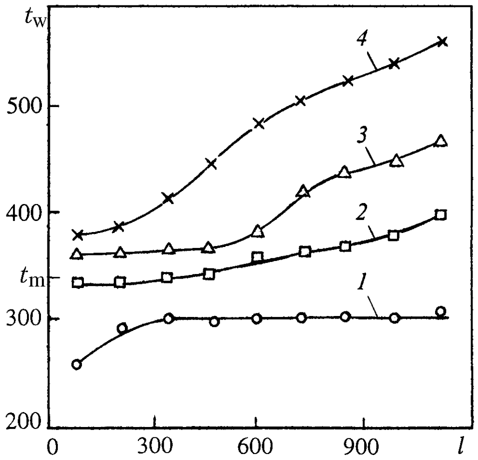

Fig. 4. Change in the wall temperature along the tube length at P = 5.0 MPa , $t_{\text{liq}}^{\text{in}}$ = 244°C, ρu = 132 kg/(m^2·sec), $d_{\text{outs}}/d_{\text{ins}}$ = 8.00/6.30 mm, and $q\cdot 10^{-5}$ W/m^2: 1) 0.30; 2) 0.69; 3) 1.78; 4) 2.27.

The experimental data on heat transfer obtained for the portions BC and CD of the plot of t_w as a function of q are described by the equations of convective heat exchange with allowance for the influence of free convection. The same plot of t_w as a function of q is obtained for the turbulent regime of motion and low temperatures of toluene (Fig. 3). However pulsations of the liquid pressure and the wall temperature accompanied by sound effects (thermoacoustic self-oscillations) appear in the experimental tube at $t_w = t_m$ (portion BC). As the heat flux increases, the pulsatory process becomes more intense and the wall temperature decreases at $t_w > 450$°C (portion DE in Fig. 3). The indicated temperature corresponds to the temperature of decomposition of toluene while the measurements of the amplitude-frequency characteristics of the process show that in this case we have a change of the pressure-oscillation frequency. As the heat flux increases further, the wall temperature changes insignificantly (portion EF in Fig. 3).

It is pertinent to note that the pulsatory regime of heat transfer is observed when the liquid is cold and the regime of motion of toluene is transient. In this case, at $t_w > 450$°C, the wall temperature either decreases or changes insignificantly with increase in the heat flux. The decrease in the wall temperature defies clear explanation. It is possible that, in addition to the change in the oscillation frequency of the liquid pressure, we have the decomposition of toluene under these conditions, which results in improved heat transfer. We were unable to describe the improved regime of heat transfer, obtained at low temperatures of toluene and accompanied by the thermoacoustic self-oscillations of pressure, by ordinary equations of convective heat exchange.

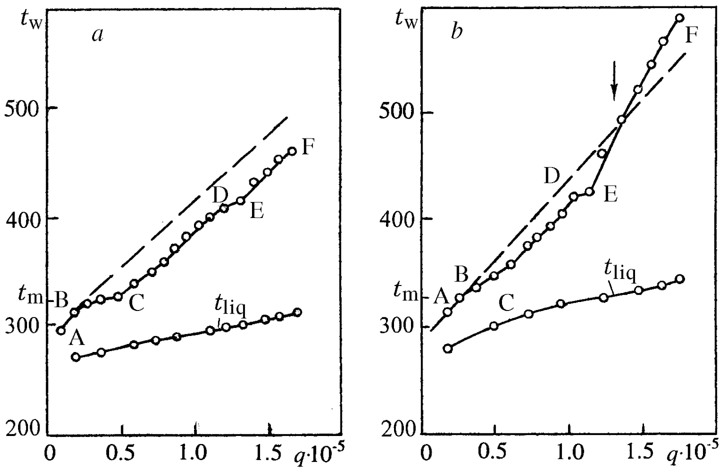

Fig. 5. Temperature of the wall and the liquid vs. heat-flux density for different lengths of the tube at P = 4.5 MPa, t_{liq}^{in} = 265°C, ρu = 91 kg/(m^2·sec), d_{outs}/d_{ins} = 8.0/6.3 mm, and l_{heat} = 300 mm: a) x/d = 17.5; b) x/d = 42.9.

We note that the laminar regime of motion (Re < 2200) is preserved at low temperatures of the liquid in short tubes with small diameters. At high temperatures of the liquid, the laminar regime of motion is observed in the initial portion of the tube while the transient and turbulent regimes of motion occur in the remaining part of it.

From the diagrams of change in the wall temperature (Fig. 4) obtained in the turbulent regime of motion of heated toluene in a long tube it follows that at $t_w < t_m$ the regularities of change in t_w along the tube length are equal for the cold and heated liquids. The distinguishing features of change in the wall temperature appear at $t_w > t_m$. In the experiment with the heated liquid, we observe an increase (characteristic of the impaired regime of heat transfer) in the wall temperature for certain values of the enthalpy of toluene and the heat absorption ($q/\rho u$) (curve 4 in Fig. 4).

The plots of t_w as a function of q obtained in the experiments with heated toluene at near-critical pressures (Fig. 5) have the same portions as in the experiments with cold toluene (Figs. 2 and 3) and show that in the initial part of the tube (x/d = 17.5) the normal regime of heat transfer is observed whereas above the central part (x/d = 42.9) the heat transfer is impaired under the influence of individual factors for certain combinations of operating conditions (in Fig. 5, the impairment of heat transfer is shown as an arrow and the normal regime is shown as a dashed line).

The possibility of the impaired regime of heat transfer of hydrocarbons occurring is described in [8].

The results obtained for different regimes of motion and different temperatures of toluene at supercritical pressures show that we have three regimes of heat transfer (normal, improved, and impaired) in the apparatuses under certain conditions which are related to many factors influencing the hydrodynamics of the flow.

Substantial changes in the thermophysical properties of the liquid and all the effects occurring in this case (change in the forces acting in the moving liquid, acceleration of the flow, free convection, intensification or decay of turbulent exchanges, pulsation of the liquid pressure, decomposition of hydrocarbon liquids, etc.) finally influence the character of flow and the intensity of heat transfer. Under certain conditions, one or several factors become predominant and the intensity of heat transfer (change in the wall temperature) depends mainly on them. Therefore, in determining the wall temperature, we must first reveal the conditions of occurrence of the process along the tube length and the possibility of occurrence of individual effects that influence the temperature regime of the wall in the case in question.

NOTATION

t, temperature, °C; P, pressure, MPa; q, heat flux, W/m^2; u, velocity m/sec; ρ, density, kg/m^3; ρu, mass velocity, kg/(m^2·sec); d, diameter, mm; l, length, mm; x, distance from the inlet of the tube, mm; t_m, temperature corresponding to the maximum of the heat capacity of a substance at supercritical pressures, °C; Re, Reynolds number.

Subscripts and superscripts: w, wall; liq, liquid; in, inlet; out, outlet; heat, heated; cr, critical; ins, inside; outs, outside; d, diameter; m, maximum.

REFERENCES

1. M. E. Shitsman, *Teplofiz. Vys. Temp.*, **1**, No. 2, 267–275 (1963).
2. Yu. V. Vikhrev, Yu. D. Barulin, and A. S. Kon'kov, *Teploénergetika*, No. 9, 80–82 (1967).
3. M. A. Styrikovich, O. I. Martynova, and Z. L. Miropol'skii, *Processes of Vapor Generation at Electric Power Plants* [in Russian], Moscow (1969).
4. N. L. Kafengauz and M. I. Fedorov, *Inzh.-Fiz. Zh.*, **11**, No. 1, 99–104 (1966).
5. F. I. Kalbaliev, F. K. Babaev, and D. P. Mamedova, *Inzh.-Fiz. Zh.*, **46**, No. 5, 716–720 (1984).
6. K. M. Abdullaev, M. A. Rzaev, and R. F. Kelbaliev, *Izv. Vyssh. Uchebn. Zaved., Neft' Gaz*, No. 1, 49–52 (1993).
7. R. I. Pepinov, R. F. Kelbaliev, and S. Sh. Babaeva, in: *Improvement of the Efficiency of Electric Power Systems and Their Elements*, Collection of Sci. Papers [in Russian], Baku (1997), pp. 178–183.
8. R. F. Kelbaliev, *Inzh.-Fiz. Zh.*, **74**, No. 2, 115–118 (2001).
9. B. S. Petukhov, V. S. Protopopov, and V. A. Selin, *Teplofiz. Vys. Temp.*, **10**, No. 2, 347–354 (1972).
10. V. A. Kurganov, *Teploénergetika*, No. 3, 2–10 (1998); No. 4, 35–44 (1998).