HEAT TRANSFER IN LAMINAR FLOW AT SUPERCRITICAL PRESSURE

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The properties of the heat transfer for $p > p_{cr}$, $t_f < t_m \gtrless t_w$ in a laminar flow of aromatic hydrocarbons are described. The results are compared with the heat transfer in the case of turbulent flow.

There have been a number of investigations of convective heat transfer in turbulent flow at supercritical pressure, confirming the existence of optimal conditions for heat transfer associated with pulsations of the fluid pressure and the wall temperature [1-6]. To explain the properties of convective heat transfer in these conditions, it is expedient to have experimental data also on heat transfer in laminar flow. However, there has not been a detailed experimental investigation of the heat transfer in laminar flow at supercritical pressure, but only some information on the heat transfer to toluene and polymethylphenyl siloxane [1, 4].

The present work is an investigation of the heat transfer to toluene ($p_{cr} = 39.2$ bar, $t_{cr} = 320.8$°C) and benzene ($p_{cr} = 47.7$ bar, $t_{cr} = 289.45$°C) for $p > p_{cr}$, $t_f < t_m \gtrless t_w$ in laminar flow; the results are compared with the turbulent flow of these fluids. The heat transfer was investigated experimentally in an ascending flow of the liquids.

The experimental apparatus and procedure are described in [2]. The experimental section of the apparatus was a stainless-steel tube with a heated length of 170 mn, wall thickness 0.5 mm, and internal diameter 3.0 mm in laminar flow and 2.0 mm in turbulent flow. Hydrodynamic-stabilization sections precede and follow the heated section.

The variation of the wall temperature over the tube length in experiments with benzene for $\rho u = 82$ kg/m^2·sec is shown in Fig. 1. It is evident that at $t_w \ll t_m$ ($t_m = 297$°C) the variation of the wall temperature over the tube length corresponds to the usual law of convective heat transfer (curve 1). With increase in the heat flux under these conditions the wall temperature increases over the whole length of the tube. Beginning at a certain value of the heat flux, the wall-temperature distribution ceases to be monotonic. In the experiments with toluene and benzene at small mass flow rates ($\rho u < 100$ kg/m^2·sec, $Re_{in} = 500$) the wall-temperature distribution ceases to be monotonic at $t_w < t_m$. As the liquid approaches t_m, the variation in t_w over the tube length becomes undulatory (curves 3 and 4).

A number of sharply expressed maxima appear over the length of the tube (curve 4). With further increase in the heat flux, a sharp increase in t_w is observed in the final part of the tube. In experiments with toluene and benzene, the distribution of the wall temperature is observed at $t_w > 400$°C (curve 5).

Note that at $t_w \approx t_m$ pulsations of the fluid pressure and the wall temperature appear and are retained on further increase in heat flux.

Certain features of the fluid-pressure pulsations were considered in [3-7]. In [5, 6] the high-frequency spontaneous oscillation is attributed to the appearance of pressure shock waves in the flow, and it is suggested that a standing wave is formed in the channel, which is confirmed in [7] on the basis of measurements in the course of boiling. The results of [5-7] show that the nonmonotonic variation of t_w over the tube length is due to the appearance of thermoacoustic pressure oscillations.

Curves of the wall temperature against the heat-flux density for toluene in conditions of laminar and turbulent flow are shown in Fig. 2. These curves were plotted for thermocouples situated a distance $l = 90$ mm from the tube inlet in laminar flow and a distance $l = 140$ mm in turbulent flow. Local values of the Reynolds number in laminar flow at these tube cross sections are given in Table 1, which corresponds to the experimental points on the curve in Fig. 2a.

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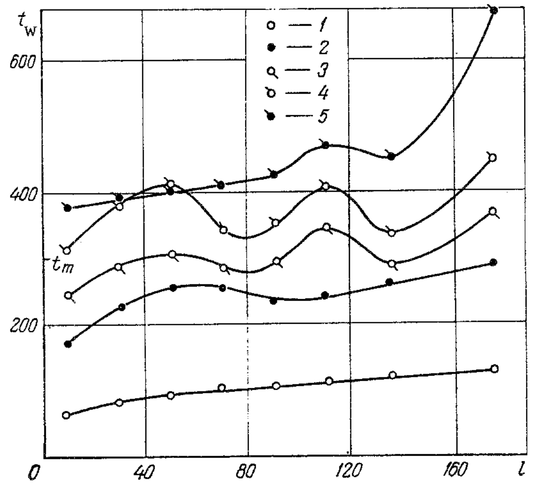

Fig. 1. Variation of wall temperature over tube length in ascending motion of benzene ($p = 55$ bar, $\rho u = 82$ kg/m^2·sec, $t_f^{in} = 20°C$): 1) $q \approx 0.36 \cdot 10^5$; 2) $1.03 \cdot 10^5$; 3) $1.45 \cdot 10^5$; 4) $2.10 \cdot 10^5$; 5) $q \approx 2.80 \cdot 10^5$ W/m^2.

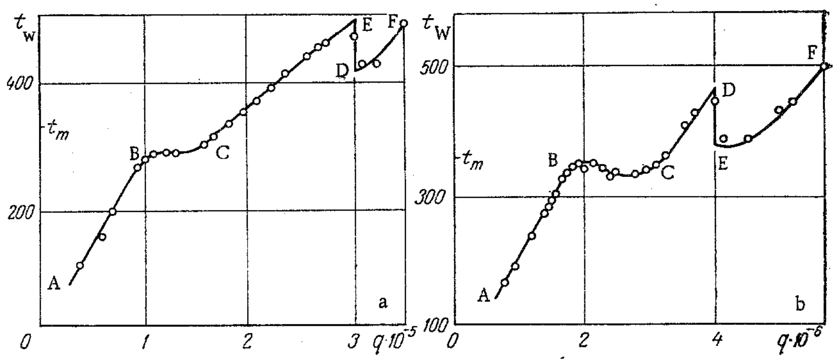

Fig. 2. Dependence of wall temperature on heat-flux density in experiments with toluene: a) laminar flow, $p = 50$ bar, $\rho u = 97$ kg/m^2·sec; $t_f^{in} = 20°C$; b) turbulent flow, $p = 60$ bar; $\rho u = 3060$ kg/m^2·sec; $t_f^{in} = 20°C$.

TABLE 1. Local Values of Reynolds Number

Expt. No.	1	2	3	4	5	6	7	8	9	10	11
Re	500	540	660	770	800	870	900	960	1040	1070	1130
Expt. No.	12	13	14	15	16	17	18	19	20	21	22
Re	1250	1280	1370	1430	1460	1500	1600	1720	1840	2040	2100

On section AB (Fig. 2a) at a wall temperature less than t_m the curve of $t_w = f(q)$ is the same as in ordinary convective heat transfer. At point B the wall temperature approaches the value of t_m for the given fluid. Beyond point B, t_w changes slowly with increase in heat flux. At the end of section BC, the wall temperature almost reaches t_m. Further increase in the heat flux is accompanied by an increase in the wall temperature (section CD).

At large heat fluxes and high wall temperatures the temperature curve changes again (section DEF). Reduction in temperature on the section DE in experiments with toluene and benzene is observed at wall temperatures around 450°C.

Comparison of Fig. 2a with Fig. 2b shows that the curve of $t_w = f(q)$ has the same general shape in both laminar and turbulent flow. The differences are the lengths and slopes of the individual sections and also the values of the heat flux.

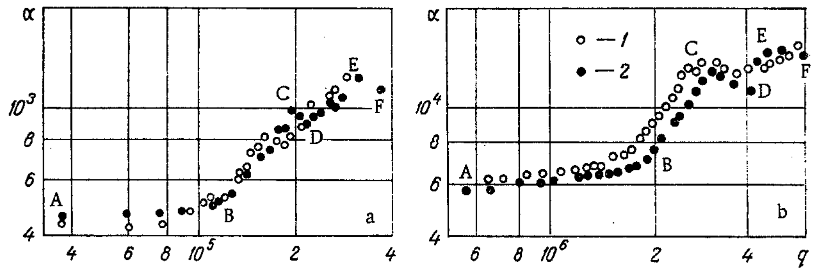

Fig. 3. Dependence of heat-transfer coefficient on heat-flux density in experiments with toluene: a) laminar flow; 1) p = 70 bar; ρu = 96 kg/m^2 · sec; t_f^{in} = 18°C; 2) p = 90 bar; ρu = 87 kg/m^2 · sec; t_f^{in} = 15°C; b) turbulent flow; 1) p = 45 bar; ρu = 3168 kg/m^2 · sec; t_f^{in} = 15°C; 2) p = 65 bar, ρu = 3060 kg/m^2 · sec; t_f^{in} = 20°C.

In turbulent flow the pulsations of the fluid pressure and the wall temperature are of larger amplitude than in laminar flow. The first appearance of pulsational conditions is at point B on the curve of $t_w = f(q)$.

Note that there is a definite correspondence between the curve of $t_w = f(q)$ and the temperature dependence of the physical properties of the material. For example, on the section AB the physical properties of the material vary only slightly and ordinary convective heat transfer is observed. After point B, when t_w approaches t_m, the physical properties of the material change more rapidly in the boundary layer (for example, c_p increases) and the heat transfer intensifies (section BC). After point C, t_w becomes larger than t_m and c_p decreases in the boundary layer; correspondingly, the heat-transfer intensity reduces somewhat (section CD). However, section DEF does not correspond to the change in physical properties of the material.

Reduction in wall temperature when $t_w > t_m$ (section DEF) has also been observed in turbulent flow in the experiments and attributed to stepwise change in the frequency of the pressure oscillations [3-6]. These investigators are also inclined to attribute the shape of the temperature curve $t_w = f(q)$ to the appearance of high-frequency pressure oscillations.

Curves of $\alpha = f(q)$ are shown in Fig. 3 for toluene in laminar and turbulent flow. The individual sections of the curves of $\alpha = f(q)$ evidently differ in laminar and turbulent conditions.

On the basis of the experimental data given above it may be concluded that at supercritical pressure in laminar flow the wall temperature does not vary monotonically. Some of the features of convective heat transfer observed for turbulent flow at $p > p_{cr}$ – in particular, the variation of the wall temperature on the curves of $t_w = f(q)$ and t_w and $f(l)$ – are also confirmed in laminar flow.

NOTATION

t_w, wall temperature; t_f, fluid temperature; t_m, temperature corresponding to maximum specific heat (pseudocritical temperature); p, fluid pressure; p_{cr}, critical pressure; l, length of heated section; ρu, mass flow rate of fluid.

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