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BURNOUT AT LARGE SUBCOOLINGS AND NEAR-CRITICAL PRESSURES OF TOLUENE

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The results of experimental investigation of a burnout of toluene at subcoolings $\Delta t = 50-270^{\circ}C$ *at the tube inlet and pressures* $P/P_{cr} = 0.70–0.94$ *are given. The critical heat fluxes as functions of the mass velocity of the liquid and its subcooling to the saturation temperature are established. The results obtained are compared to the data for water.*

Boiling of liquids occurs in numerous steam-generating apparatuses of the chemical and petroleum industries and steam generators of thermal and nuclear power plants; it also takes place in other branches of modern engineering.

The reliability of heat-exchange apparatuses operating in the regime of boiling of a liquid largely depends on correct selection of the parameters precluding the occurrence of a burnout. In this connection, one must have reliable data for calculation of critical heat fluxes, whose regularities in forced channel motion of a liquid have been studied fairly well; some of them have been presented in [1–5]. A large number of experimental results on burnout have been obtained in experiments with water. At the same time, such results for other liquids, in particular, for hydrocarbons, are few in number, despite the wide use of these substances.

Creation of new steam-generating apparatuses operating in the petroleum and chemical industries requires that the regularities of burnout for different hydrocarbons be known. Experimental investigation of this process for the liquids indicated is very difficult. Therefore, in studying burnout, it is desirable to select (as a model liquid) a hydrocarbon based on which other hydrocarbons finding use in engineering are formed. The most suitable in this respect are aromatic hydrocarbons, whose typical representative is toluene ($P_{cr} = 4.24$ MPa and $t_{cr} = 320.8^{\circ}C$).

Experimental values on the burnout of toluene supplement and extend knowledge of the regularities of the critical heat flux obtained for other liquids, in particular, water.

The values on the burnout of liquids can arbitrarily be subdivided into the following two groups:

(1) the values found for a saturated liquid and corresponding to the operating conditions of steam-generating units;

(2) those obtained for a subcooled (to the saturation temperature) liquid, which correspond to the conditions of cooling of the high-temperature apparatus surface.

In our work, an experimental study is made of the burnout of a strongly subcooled toluene in the region of nearly critical pressures and the results obtained are compared to the analogous results for water.

The experiments have been carried out on a setup operating by the principle of an open circuit. All the units of the setup, which are in contact with the heat-transfer agent under study, are manufactured of 1Kh18N10T stainless steel. Circulation of the liquid in the circuit is created by a four-plunger pump. Three stabilizing tanks are connected in series in the system to prevent a pressure pulsation. The system has provision for a liquid-recirculation line. The liquid arrives at the inlet of the pump from a pressure tank, successively passes through the stabilizing tanks, and finds itself in the working portion. In the diagram, there is a refrigerator for cooling of the hot product at the pump inlet.

As the experimental portion we have employed stainless-steel tubes with a total length of 500–1000 mm, diameters of $d_{out} = 6$ mm and $d_{in} = 4$ mm, and a heated length of $l = 300–800$ mm.

The wall of the tube (of the experimental portion) and of the preheater is heated by an electric current. The pressure of the liquid at the inlet and outlet of the experimental portion was measured by standard pressure gauges.

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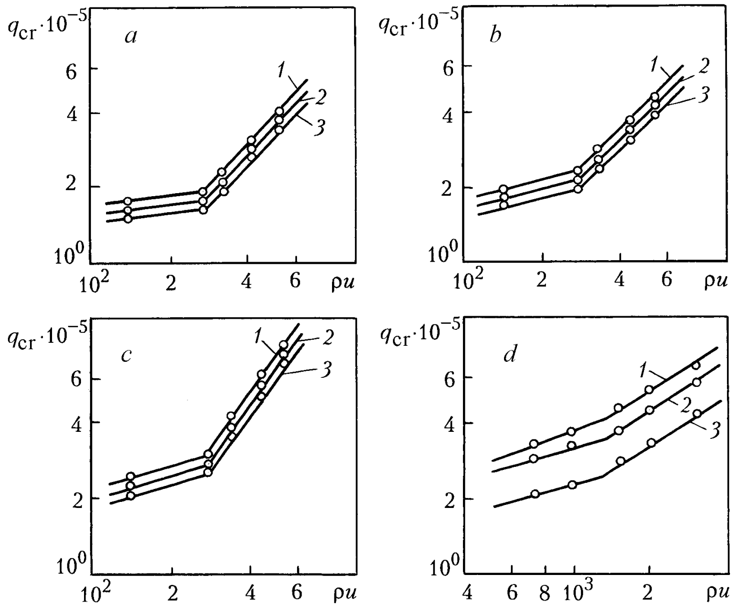


Fig. 1. Critical heat flux of toluene (a, b, c) and water (d) vs. mass velocity at different pressures [1) P/P_{cr} = 0.70; 2) 0.82; 3) 0.94] and subcoolings [a) Δt = 66; b) 106, c) 222, d) 75^{o}C].

The flow rate of the liquid was measured by the volume method. The temperature of the liquid at the points indicated above and the temperature of the tube wall were determined with Chromel-Alumel thermocouples whose readings were recorded by a potentiometer. A KSP-4 recorder was employed for monitoring and recording of the temperatures.

The setup was calibrated with water and toluene. The results obtained were checked with the well-known equations of Petukhov [4]

$$\mathrm{Nu} = 1.31 \left(\frac{1}{\mathrm{Pe}} \frac{X}{d} \right)^{-1/3} \left(1 + 2 \frac{1}{\mathrm{Pe}} \frac{X}{d} \right) \left(\frac{\mu_w}{\mu_{liq}} \right)^{-1/6}$$

and Kutateladze [1, 6]

$$q_{cr} = \frac{d}{4l} \rho u \, (rx + \Delta i_{inl}) \, .$$

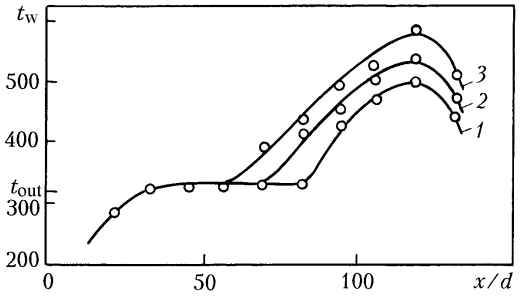
The disagreements between the experimental and calculated data were no higher than 6%, which enabled us to consider the values obtained as being reliable. Before the processing of the experimental results, we checked the thermal balance. The quantity of heat lost by the electric heater and that received by the liquid differed by no more than 5%.

The experimental portion was installed vertically, and the liquid moved from the bottom upward.

The experiments were carried out in the following ranges of variation of the operating parameters: P/P_{cr} = 0.70–0.94, ρu = 150–600 kg/(m^2·sec), $\Delta t/t_{cr}$ = 0.20–0.90, and q_{cr} = (1.5–9.0)·10^5 W/m^2.

When the operating parameters (P, t_{liq}, t_w, and ρu) are constant, the subcooling of the liquid decreases along the tube length with increase in the heat flux and we have a burnout for certain values of the latter. The onset of the burnout is recorded from a sharp increase in the wall temperature in a certain cross section of the tube. In a number of works ([1, 2]), for the convenience of calculation of the critical value of the heat flux the subcooling of a liquid has been determined from the temperature of the liquid at the inlet to the tube. We analogously calculate the subcooling of toluene in computing the critical heat flux.

The critical heat fluxes as functions of the mass velocity for different subcoolings of toluene show that the critical heat flux increases with mass velocity and subcooling in the region of nearly critical pressures (Fig. 1). For



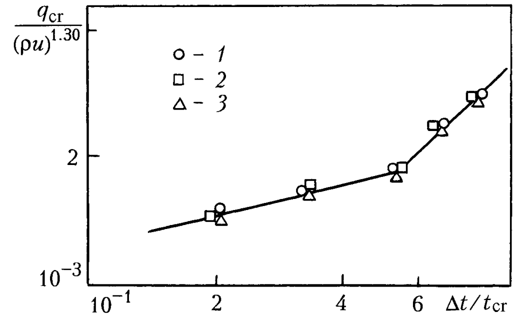


Fig. 2. Change in the wall temperature along the tube length at P/P_{cr} = 0.94, Δt = 178°C, ρu = 520 kg/(m^2·sec), and different heat fluxes: 1) $q = 5.15\cdot10^{-5}$; 2) 6.30; 3) 7.00 W/m^2.

Fig. 3. Dependence $q_{cr}/(\rho u)^{1.30} = f(\Delta t/t_{cr})$ for ρu = (250–520) kg/(m^2·sec) and different P/P_{cr}: 1) 0.70; 2) 0.82; 3) 0.94.

example, at the same pressures (P/P_{cr} = 0.94) and subcoolings (Δt = 66°C) of toluene, the critical heat flux increases from $1.2\cdot10^5$ to $3.3\cdot10^5$ W/m^2 with increase in the mass velocity from 150 to 520 kg/(m^2·sec).

The data on the critical heat flux, obtained for water and presented in Fig. 1d, have been taken from [3] and confirm the validity of this regularity. However, according to the experimental results for toluene, q_{cr} as a function of ρu has different regularities for small ($\rho u \le 250$ kg/(m^2·sec)) and large ($\rho u \ge 250$ kg/(m^2·sec)) mass velocities. As the velocity of motion of the liquid increases, the process of exchange between the liquid and the vapor in the wall layer of the turbulent flow becomes more intense, which contributes to the increase in q_{cr}. For high velocities of circulation of the liquid the convective components of the transfer of heat are much larger than those for low velocities.

In [6], based on the available data on q_{cr}, the increase in the critical heat flux with circulation velocity is further explained by the fact that the liquid forced out from the wall layer must be accelerated to the velocity of the flow core. The work on displacing the liquid increases and the critical heat flux increases accordingly. For small velocities of motion of the liquid the influence of the factors indicated above on the values of the critical heat flux is weaker; accordingly, the dependence $q_{cr} = f(\rho u)$ has dissimilar slopes for small and large circulation velocities.

From Fig. 1d, it follows that the same regularity of the dependence $q_{cr} = f(\rho u)$ is observed for water but the point of inflection is produced when $\rho u > 1000$ kg/(m^2·sec). We assume that, in addition to the data for water, one must have the values of the critical thermal load for other liquids. The experimental results on the burnout of toluene and water which have been obtained in the region of nearly critical pressures (P/P_{cr} = 0.70, 0.82, and 0.94) (Fig. 1) show that the dependence of the wall temperature on pressure is variable in character. Away from the critical pressure of the liquid, the wall temperature increases abruptly in the process of burnout, whereas at near-critical pressures its increase has a smooth retarded character (Fig. 2) [7].

The influence of the subcooling or of the change in the steam content on the critical heat flux at different pressures and mass velocities is also illustrated in Fig. 1. In the experiments with both other liquids and toluene, an increase in the steam content prevents the liquid from the core from penetrating to the channel wall and, as a consequence, the value of the critical heat flux drops with decrease in the subcooling of the liquid.

In the region of near-critical pressures, q_{cr} as a function of the mass velocity for different subcoolings of toluene can be represented in the form $q_{cr} \sim (\rho u)^n$, where $n \approx 1.30$, for $\rho u > 250$ kg/(m^2·sec) (Fig. 3). It follows from the plot that we have $q_{cr} \sim (\Delta t/t_{cr})^{0.22}$ for small subcoolings ($\Delta t/t_{cr} < 0.55$) and $q_{cr} \sim (\Delta t/t_{cr})^{1.20}$ for large subcoolings ($\Delta t/t_{cr} > 0.55$).

CONCLUSIONS

1. We have investigated experimentally the burnout of a subcooled toluene in a tube in the region of nearly critical pressures. The results obtained were compared to the data for water. Certain regularities of the burnout of a subcooled liquid have been revealed.

2. Different characters of change of the critical heat flux $q_{cr} = f(\rho u)$ for low and high mass velocities of a subcooled liquid have been established.

3. Different degrees of influence of a small and large subcooling of a liquid on the critical heat flux have been revealed.

NOTATION

t, temperature, $^{\circ}$C; P, pressure, MPa; q, heat flux, W/m^2; u, velocity, m/sec; ρu, mass velocity, kg/(m^2·sec); l, tube length, mm; μ, dynamic viscosity, N·sec/m^2; X, distance from the inlet to the tube, mm; d, tube diameter, mm; $\Delta t = t_{sat} - t_{liq}$, subcooling of the liquid to the saturation temperature, $^{\circ}$C; t_{liq}, inlet temperature of the liquid, $^{\circ}$C; $\Delta i = i_{sat} - i_{liq}$, enthalpy difference, kJ/kg; x, steam quality (of the relative enthalpy); r, heat of evaporation, kJ/kg; Nu and Pe, Nusselt and Péclet numbers. Subscripts: w, wall; liq, liquid; in, inside; out, outside; cr, critical; inl, inlet; sat, saturation.

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