NATURE OF HEAT EXCHANGE AND HYDRAULIC RESISTANCE UNDER CONDITIONS OF FORCED MOVEMENT OF A LIQUID AT SUPERCRITICAL PRESSURE

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The results are presented of an experimental study of hydraulic resistance and high-frequency pulsations in pressure arising during the process of heat exchange at supercritical pressure of n-heptane as a function of wall temperature, flow rate, and length of the working channel.

There are a number of works published in the current literature devoted to a study of heat exchange at supercritical parameters under conditions of forced fluid movement. The results of the published works do not present a uniform picture. One author observed a system in which the heat-exchange coefficients were considerably higher than those calculated from the known equations of convective heat exchange [1-3], others observed systems with poorer heat exchange. The given deviations were explained either by the effect on the heat exchange of a change in physical properties [4] or by the effect of free convection [5]. The effect of free convection on the decrease in heat exchange in the supercritical region was persuasively confirmed experimentally [6]. It must be assumed that the effect of the natural convection will develop for the most part at low current velocities.

The results of an experimental study of the heat-exchange process during forced movement of n-heptane over a wide range of current velocities (5-30 m/sec) at supercritical pressure ($P/P_{cr} = 1.45$) are presented in this article. The joint consideration of heat exchange, hydraulic resistance, and high frequency pressure pulsations arising during the heat-exchange process allows one to show the presence of principles demonstrating that the mechanism of heat exchange at supercritical parameters as a function of the hydrodynamics of the current has a varied nature.

The experiments were conducted on 0Kh18N10T steel tubes 2.02/2.52 mm in diameter (the length of the heated section was 40 and 100 mm), and on tubes 2.4/3.0 mm in diameter (length of heated section 40 mm). Measurements of the characteristics of the heat exchange, hydraulic resistance in the working section, and high-frequency pressure pulsations arising during the heat-exchange process were conducted synchronously during the experiments.

The design of the apparatus is described in [7]. Measurement of the hydraulic resistance was conducted using DM-6 and EPID instruments with maximum scales of 1, 2.5, and 6.3 atm, as well as a U-shaped mercury differential manometer. The experiments were conducted both with rising and dropping movement of the liquid.

The experimental data obtained on the 2.02/2.52 mm tube are presented in Fig. 1 in the form of the dependence of the wall temperature on the heat flux $t_w = f(q)$ and of the hydraulic resistance on the heat flux in relative coordinates $\Delta P/\Delta P_0 = f(q/q_m)$ for the same experiments.

As seen from Fig. 1, at low current velocities (5 m/sec) in the region of wall temperatures above t_m the heat exchange is characterized by a sharp increase in hydraulic resistance ($\Delta P \sim q^{2.4}$) and an insignificant improvement in heat exchange. The increase in resistance can evidently not be explained by increased mass exchange between the boundary layer and center of the current. In these experiments

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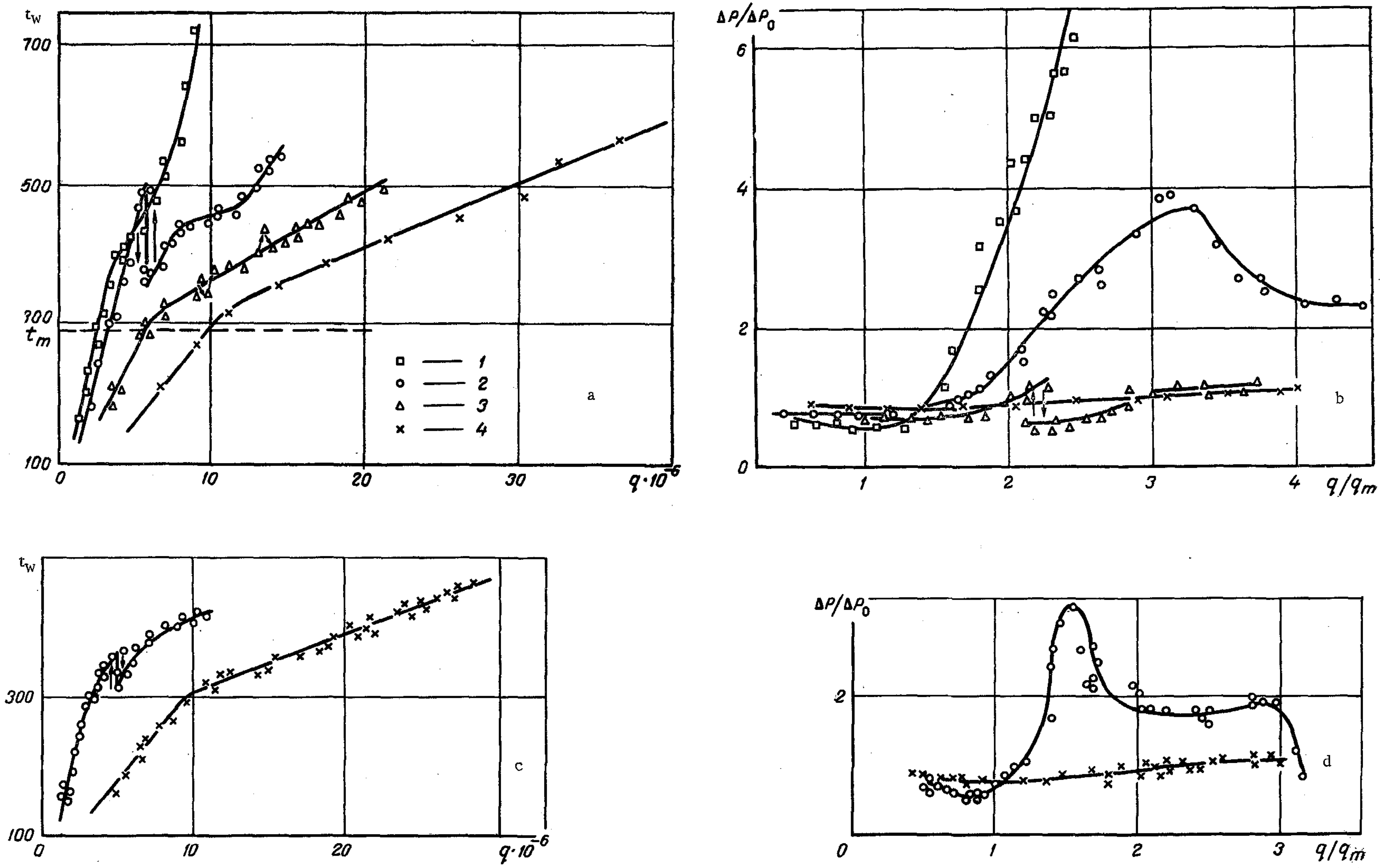

Fig. 1. Dependence of wall temperature (a, c) and hydraulic resistance (b, d) on heat flux (d = 2.02/2.52 mm, t_l = 20°C): a, b) l_h = 40 mm; c, d) l_h = 100 mm; 1) 5; 2) 10; 3) 15; 4) 30 m/sec; t_w, °C; q, W/m^2.

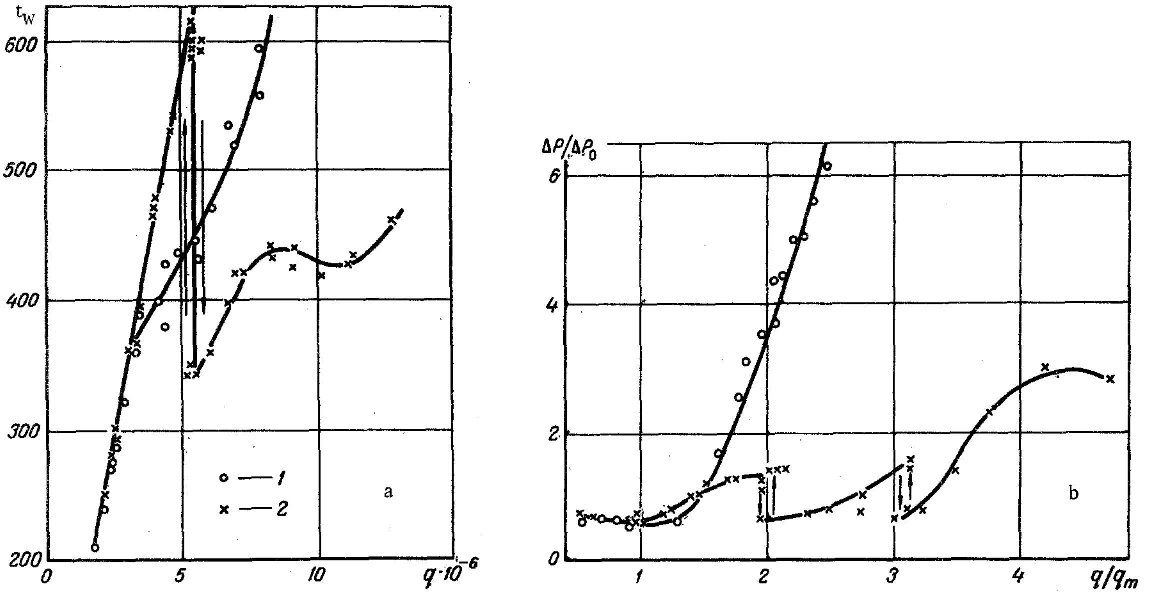

Fig. 2. Effect of forced movement of liquid on heat exchange (a) and hydraulic resistance (b) (v = 5 m/sec, t_l = 20°C, d = 2.02/2.52 mm, l_h = 40 mm): 1) rising movement; 2) dropping movement. t_w, °C; q, W/m^2.

when the wall reached a temperature $t_w \geq t_m$ high-frequency pressure pulsations appeared with a fundamental frequency of 4000 Hz. With an increased heat load the pulsation frequency dropped to 2000 Hz while the amplitude grew. The maximum amplitude of the pressure oscillations was $1.67 \cdot 10^5$ N/m^2.

A change in the nature of the heat exchange was observed at a current velocity of 10 m/sec. Up to a wall temperature of 500°C (at $q = 5.8 \cdot 10^6$ W/m^2) there is almost no deviation from convective heat exchange, although when the wall temperature exceeded the value t_m, just as with low current velocities, there appeared high-frequency pressure pulsations with a fundamental frequency of 4000 Hz, the amplitude of which grew with an increased heat load. The maximum amplitude of the pressure oscillations was $1.67 \cdot 10^5$ N/m^2. Upon reaching 400°C a sharp drop in wall temperature to 350°C occurred, which was accompanied by an abrupt change in the frequency of the pressure oscillations from 4000 to 8000-10,000 Hz.

With a further increase in the heat load a "plateau" was observed characteristic of boiling; the improvement in heat exchange was accompanied by an increase in the hydraulic resistance ($\Delta P \sim q^{1.67}$).

At a current velocity of 30 m/sec there characteristically appeared a considerable intensification in heat exchange with almost no growth in hydraulic resistance ($\Delta P \sim q^{0.2}$). The heat exchange in these experiments was accompanied by high-frequency pressure oscillations with a broad spectrum of frequencies (2000-20,000 Hz). The amplitude of the oscillations increased with growth in the heat load; its maximum value was $0.1 \cdot 10^5$ N/m^2.

Evidently, the mechanism of heat exchange at current velocities of 10 and 30 m/sec differs. This point of view is confirmed by experiments at 15 m/sec, in which fluctuations with time, characteristic for transitional region, were observed in the wall temperature, hydraulic resistance, and high frequency pressure pulsations accompanying the heat-exchange process.

The nature of the heat exchange in tubes with a heated length of 100 mm was the same as for tubes of length 40 mm. As is seen, an increase in current velocity from 10 to 30 m/sec in this case led to a change in the heat-exchange mechanism.

A similar picture was observed in the experiments on tubes 2.4/3.0 mm in diameter.

The results of experiments obtained with rising and dropping movements at a current velocity of 5 m/sec are compared in Fig. 2. As is seen, the substitution of rising motion for dropping led to a change in the nature of the heat exchange. While for upward motion a sharp increase in hydraulic resistance with an insignificant improvement in heat exchange was noted in the region of wall temperatures $t_w > t_m$, with downward movement a change in the nature of the heat exchange was observed upon reaching a wall temperature of 600°C similar to that noted with upward movement at current velocities of 10 m/sec.

A control series of experiments was conducted characterizing the change in the pressure drop as a function of the heat flux under conditions of surface boiling of the n-heptane at a pressure of $10 \cdot 10^5$ N/m^2. It was found that the hydraulic resistance upon boiling is proportional to the heat flux raised to the power 0.75 ($\Delta P \sim q^{0.75}$), which is in good agreement with the data presented in [8].

The experimental material presented provides a basis for assuming that at supercritical pressure at values of the wall temperature $t_w > t_m$ and liquid temperature $t_l < t_m$ three systems of heat exchange can be distinguished as a function of the current velocity.

At low current velocities ($v \leq 5$ m/sec) the heat exchange is characterized by a sharp growth in hydraulic resistance with a negligible improvement in heat exchange. It is possible that the growth in hydraulic resistance is caused for the most part by an increase not in molar transport but in the second coefficient of viscosity determined by dissipation of energy through expansion and contraction of the medium [9] which takes place in the boundary layer at supercritical pressures.

An increase in current velocity to 10 m/sec or the substitution of downward movement for upward at 5 m/sec led to a change in the nature of the heat exchange. In this case there was observed a "plateau," characteristic of boiling. The intensification of heat exchange may be caused by an increase in molar transport in a direction normal to the heating surface, indicated by the growth in hydraulic resistance.

The change in the nature of the heat exchange is evidently connected with the loss in stability of the hydrodynamics of the current in the boundary layer. A similar form has been named "pseudoboiling" [1].

At high current velocities ($v > 15$ m/sec) the intensification of the heat exchange cannot be explained by increased molar transport, since there is characteristically no change in hydraulic resistance with a growth in the heat load. In this case heat transfer evidently has another mechanism.

The function of heat carrier in a boiling liquid may be provided by phonon-carriers of acoustical energy arising as a consequence of thermal oscillations in the molecular lattice which periodically form and breaks up [10]. It can be anticipated that intensification of heat exchange in the region of high current velocities is explained to a considerable extent by a drop in the thermal resistance of the boundary layer because of supplementary heat transfer by phonon-carriers of acoustical energy.

It should be noted that the explanation of this form of heat exchange presented in this article is still insufficiently clear. Further study of the mechanism of heat exchange will evidently allow one to present more indications of the validity of the mechanism given.

NOTATION

t_w	is the wall temperature;
t_l	is the liquid temperature at the tube entrance;
t_m	is the temperature of the heat capacity maximum;
q	is the heat flux;
q_m	is the heat flux at $t_w = t_m$;
P	is the pressure in the working section;
P_{cr}	is the critical pressure;
ΔP	is the pressure drop in the working section;
ΔP_0	is the pressure drop at $q = 0$;
v	is the current velocity;
d	is the tube diameter;
l_h	is the length of the heated section.

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