# ONE POSSIBLE MODEL FOR THE TRANSFER PROCESS IN THE NEAR-CRITICAL STATE OF A LIQUID

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UDC 536.24

The results of an experimental investigation into the hydraulic resistance and pressure fluctuations of n-heptane arising in the course of heat transfer under a hypercritical pressure are presented in relation to the pressure, the rate of flow, and temperatures of the wall and liquid.

In fully-developed turbulent flow, heat transfer takes place chiefly as a result of molar transport. An increase in the heat-transfer intensity is associated with a loss of energy by friction. The existence of two modes of heat transfer in the near-critical state of the liquid was established in [1, 2]; in these two cases the laws governing the changes in hydraulic resistance and heat-transfer intensity were incapable of being explained by the Reynolds analogy.

A characteristic of the first mode ($w = 5$-$6$ m/sec) was a sharp rise in hydraulic resistance, while the heat-transfer intensity remained practically constant. An increase in the hydraulic resistance took place when the wall temperature exceeded $t_m$, the heat transfer being accompanied by pressure fluctuations with a fundamental frequency of 2000-3000 Hz; the intensity of the fluctuations increased together with the thermal loading. The second mode was characterized by an increase in the heat-transfer coefficient (by more than a factor of 2), with hardly any rise in the hydraulic resistance. This took place on increasing the rate of flow to above 15 m/sec and was accompanied by a rise in the pressure-fluctuation frequency.

In this paper we shall present the results of an experimental investigation into the heat transfer, hydraulic resistance and pressure fluctuations of a liquid as functions of the temperature and pressure of the liquid under various hydrodynamic conditions. The working liquid was n-heptane, $P_{cr} = 27.01$ atm, $t_{cr} = 267.01°C$ [3]. The work was carried out in the apparatus described in [4]. In these experiments we used working tubes made of OKh18N9T steel 2.02/2.52 and 2.4/3.0 mm in diameter. The total length of the working tubes was 160 mm, the heated part in the middle of the tube was 40 mm long. The pressure drop was measured at a distance of 94 mm (33 mm from the tube inlet and outlet). The resistance in the cold parts was subtracted after calculating its value from the Darcy equation.

We studied the effect of the temperature of the liquid on heat transfer for flow rates of 5, 10, and 30 m/sec and a pressure of $40.2 \cdot 10^5$ N/m$^2$. The results of the experiments are presented in Fig. 1.

We see that, for a flow rate of 5 m/sec, in the case of a cold liquid, the hydraulic resistance increased by approximately 8.5 times for wall temperatures exceeding $t_m$. On heating the liquid at the working-tube inlet to 140°C no such rise in hydraulic resistance was found. It was a characteristic feature that the intensity of the pressure fluctuations in the experiments with the hot liquid fell by approximately 11 times by comparison with the experiments with the cold liquid, while the fundamental frequency increased from 2500-3200 to 5100 Hz. The intensity of heat transfer in the experiments with the hot liquid remained unchanged over the whole range of wall temperatures studied (up to 560°C), despite the fact that pressure fluctuations developed for $t_w \geq t_m$.

For a flow rate of 10 m/sec ($t_l = 20°C$), high-frequency pressure fluctuations with a fundamental frequency of 4060 Hz developed in the system when the wall temperature reached $t_m$. The intensity of

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 27, No. 3, pp. 409-415, 1974. Original article submitted March 26, 1974.

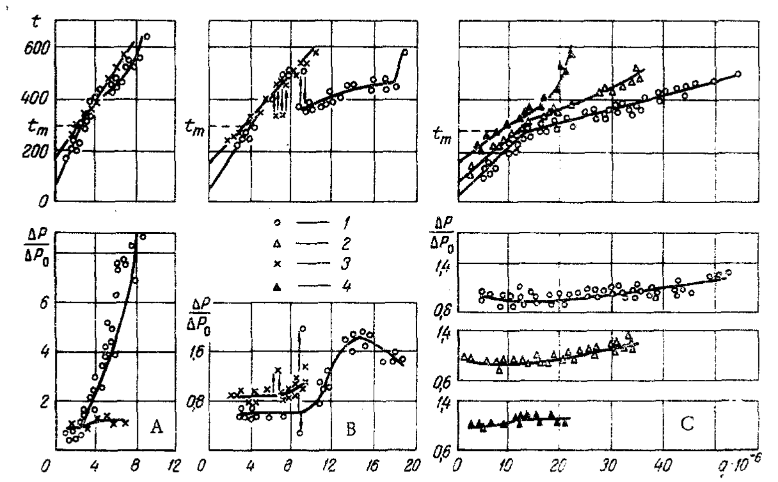

Fig. 1. Heat transfer and hydraulic resistance as functions of the rate of flow and the temperature of the liquid (P = 40.2 $\cdot 10^5$ N/m$^2$, d = 2.02/2.52 mm): A) 5; B) 10; C) 30 m/sec; 1) 20; 2) 90; 3) 140; 4) 170°C; $t_w$ °C; q, W/m$^2$.

heat transfer and the hydraulic resistance remained practically constant up to $t_w \approx 480$°C. Further increase of the thermal loading led to a sharp fall in wall temperature (to 350°C), accompanied by a change in the spectrum of pressure fluctuations; instead of a fundamental frequency of 4060 Hz, the higher frequency of 8130 Hz appeared. The mode of heat transfer was unstable; in individual cases for a constant thermal loading there was a periodic reduction and increment in the wall temperature; the hydraulic resistance and pressure fluctuations changed correspondingly. Further increase of the thermal loading led to the establishment of an improved mode of heat transfer. The intensification of the heat transfer was accompanied by a rise in hydraulic resistance. However, on increasing the thermal flux above $14 \cdot 10^6$ W/m$^2$ the hydraulic resistance fell slightly, while the intensity of heat transfer continued rising.

When the temperature of the liquid at the working tube inlet was raised to 140°C, hardly any changes in heat-transfer intensity and hydraulic resistance were observed, despite the fact that the wall temperature rose to 600°C. For values of $t_w \geq t_m$ the heat transfer was accompanied by fluctuations with a fundamental frequency of 5100 Hz.

In individual cases there was a certain instability of the values of $t_w$, the hydraulic resistance, and the spectrum of the pressure fluctuations; however, increasing the thermal load did not lead to the establishment of any improved mode of heat transfer, such as occurred in the experiments with the cold liquid. The intensity of the pressure fluctuations in the experiments with the hot liquid was 2.6 times lower than with the cold.

For a flow rate of 30 m/sec, experiments were carried out with three values of the liquid temperature at the inlet into the working tube, 20, 90, and 170°C. In the case of a cold liquid we found a considerable intensification of heat transfer; the heat-transfer coefficient increased by a factor of 2.3 as compared with the value immediately preceding the onset of the improvement in heat transfer. The hydraulic resistance rose by a factor of 1.2 by comparison with the value obtained for isothermal flow. The heat transfer was accompanied by pressure fluctuations with a wide frequency spectrum (200–20480 Hz), the fluctuations with frequencies of 200–2560 Hz being observed even before applying the thermal load. On increasing the load above $30 \cdot 10^6$ W/m$^2$, ultrasonic oscillations appeared at 60–70 kHz. It was a characteristic feature that the intensification of heat transfer started for wall temperatures of slightly below $t_m$. On increasing the temperature of the core of the flow the degree of intensification of the heat transfer diminished, and so did the intensity of the pressure fluctuations.

The effect of pressure on the heat-transfer process in the hypercritical region was studied at $t_l$ = 20°C. The pressure was $29.4 \cdot 10^5$ or $88.2 \cdot 10^5$ N/m$^2$ for a flow rate of 6 m/sec, and $40.2 \cdot 10^5$ or $84.3 \cdot 10^5$ N/m$^2$ for 30 m/sec. The results of the experiments are shown in Fig. 2. We see that for near-critical pressure of $P/P_{cr} = 1.08$ and a flow rate of 6 m/sec, for which the wall temperature exceeded $t_m$, there was a sharp rise in the hydraulic resistance. For a thermal flux equal to $6 \cdot 10^6$ W/m$^2$ the hydraulic resistance increased by a factor of 30 by comparison with its value at q = 0. The increase in hydraulic

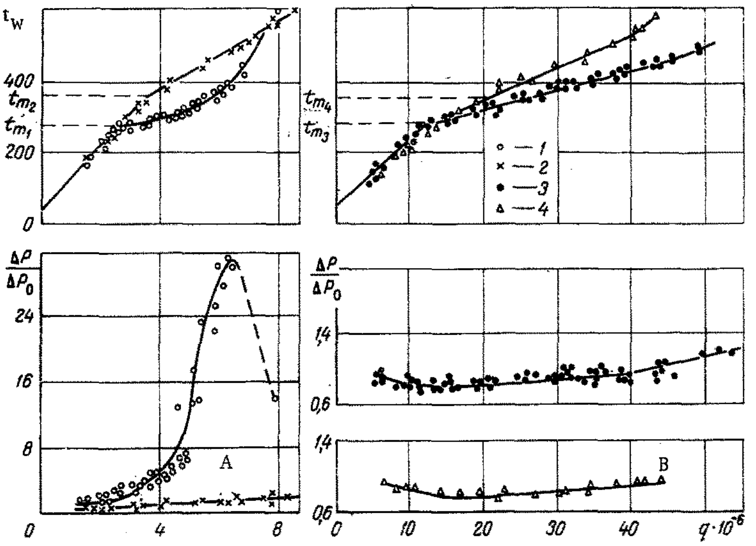

Fig. 2. Heat transfer and hydraulic resistance as functions of the rate flow and static pressure ($t_l$ = 20°C, for A) d = 2.4/3.0; B) 2.02/2.52 mm: A) 6; B) 30 m/sec; 1) $29.4\cdot 10^5$; 2) $88.2\cdot 10^5$; 3) $40.2\cdot 10^5$; 4) $84.3\cdot 10^5$ N/m$^2$.

resistance was accompanied by intense (up to 62 dB)* pressure fluctuations with a fundamental frequency of 2500-3200 Hz. For a pressure of $88.2\cdot 10^5$ N/m$^2$ there was no serious increase in the hydraulic resistance; heat transfer at $t_w > t_m$ was accompanied by pressure fluctuations at a fundamental frequency of 4000 Hz. The maximum intensity of the fluctuations fell by a factor of 4.1 on increasing the pressure from $29.4\cdot 10^5$ to $88.2\cdot 10^5$ N/m$^2$. It should be noted that the wall temperature at which intensification of the heat transfer began depended on the pressure and corresponded to $t_m$.

For a flow rate of 30 m/sec the values of $t_w$ at which improved heat transfer began depended very little on pressure; the improved heat transfer at high pressures started for wall temperatures of under $t_m$. The increase in the intensity of heat transfer was accompanied by pressure fluctuations with a wide spectrum of sound frequencies (200-20000 Hz); the low-intensity fluctuations at a frequency of 200-5000 Hz appeared even before application of the thermal load. An increase in pressure from $40.2\cdot 10^5$ to $84.3\cdot 10^5$ N/m$^2$ led to a reduction in the degree of intensification of heat transfer in the range $t_w > t_m$. At the same time there was a reduction in the intensity of the pressure fluctuations.

It follows from the experimental material presented that the sharp rise in the hydraulic resistance encountered at low flow rates, and also the considerable increase in the heat-transfer coefficient found in the case of high flow rates, took place mainly at low temperatures of the liquid. On increasing the temperature of the core of the flow, these characteristic changes in heat-transfer intensity and hydraulic resistance appeared to less marked degree, or indeed not at all. On increasing the temperature of the liquid the intensity of the high-frequency pressure fluctuations arising in the course of heat transfer also diminished. Analysis of these data suggests that one of the possible sources of pressure fluctuations may be thermal motion in the liquid. It is well known that the character of the thermal motion in the liquid is due to its structure. In a certain temperature range close to the melting point the character of the thermal motion in the liquid remains similar to that in the corresponding solid. Among the various frequencies of thermal vibrations in solids (and partly in liquids) both sonic and supersonic vibrations may occur [5]. In liquids these vibrations should appear mainly in the case of the rapid heating of individual moles of a relatively cold liquid, i.e., the case in which the heating time is shorter than the time of structural relaxation. The fluctuations so arising may interact with the medium in the boundary layer (which exists at a pseudocritical temperature), as a result of which an increase in heat-transfer intensity takes place.

If the thermal motion in the liquid makes a substantial contribution to the formation of the sonic wave for $P > P_{cr}$, for precritical pressures also (and for the same reason) we should expect a development of fluctuations, which under certain conditions might influence the transport processes. An influence of this kind would be expected under conditions promoting the rapid heating of individual moles of a

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* As zero dB in the spectrometer we took 1 mV, which corresponded to a pressure of 353 N/m$^2$.

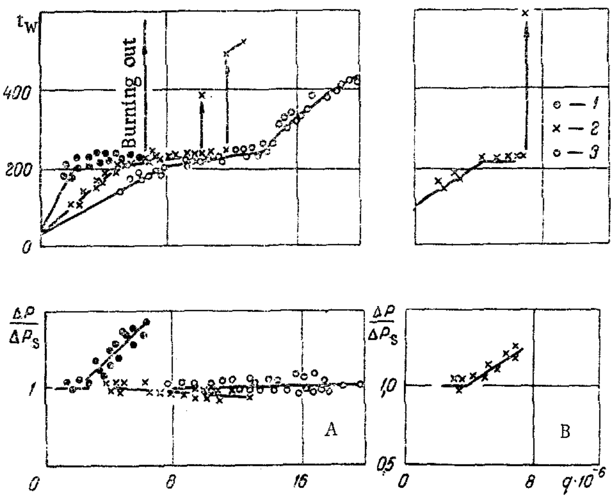

Fig. 3. Heat transfer and hydraulic resistance in relation to the flow rate and temperature of the liquid at a precritical pressure (P = 10.8 $\cdot 10^5$ N/m$^2$, for 1, 2) d = 2.4/3.0; for 3) d = 2.02 /2.52): A) 25; B) 100°C; 1) 5; 2) 16; 3) 30 m/sec.

relatively cold liquid. In order to verify the reliability of this proposition, we carried out some experiments on n-heptane at a precritical pressure $P/P_{cr} = 0.4$, for flow rates of 5-30 m/sec and temperatures of the liquid at the inlet of the working tube equal to 25 and 100°C. The results of the experiments are shown in Fig. 3.

We see that for a liquid temperature of 25°C (in the case of a flow velocity of 5 m/sec) the increase in the heat-transfer intensity was accompanied by an increase in the hydraulic resistance ($\Delta P \sim q^{0.7}$), characteristic of bubble-type boiling. The transition from the bubble to the film type of boiling was accompanied by a sharp jump in wall temperature, and the experiment ended in the burning-out of the working tube. It should be noted that on the initial section of the bubble-type boiling characteristic no pressure fluctuations occurred; only for $q = 3.5 \cdot 10^6$ W/m$^2$ did pressure fluctuations develop, with a fundamental frequency of 1600 Hz and an intensity of 35-40 dB. For flow rates of 16 and 30 m/sec the character of the relationship between the hydraulic resistance and the thermal flux altered. The increase in the heat-transfer intensity for wall temperatures exceeding $t_s$ was not accompanied by any increase in the hydraulic resistance. For high flow rates and a liquid temperature of 25°C, pressure fluctuations were recorded even before application of the electrical load. Thus at 16 m/sec, in the case of "isothermal" flow, fluctuations with a fundamental frequency of 10,000 Hz and a maximum intensity of 25 dB developed. On smoothly applying the electric load the intensity of the fluctuations then diminished, and in individual experiments the fluctuations vanished for wall temperatures slightly below $t_s$, only appearing with a fundamental frequency of 6400 Hz in the middle of the "plateau" at $q = 7.0 \cdot 10^6$ W/m$^2$. The intensities of the fluctuations then increased with increasing thermal load, the maximum value being 53 dB. The transition to the inferior mode of heat transfer was not accompanied by any severe change in the spectrum of pressure fluctuations detected. For a flow rate of 30 m/sec ("isothermal" flow) a spectrum of pressure fluctuations at frequencies of 200-5000 and 20,000 Hz was observed, with a maximum intensity of 20 dB. For $q = 9.3 \cdot 10^6$ W/m$^2$ a wide spectrum of sonic frequencies developed, the intensity of these increasing with increasing thermal load. The maximum intensity of the pressure fluctuations was 40-45 dB. It should be noted that the degree of worsening of the heat transfer at the crisis diminished with increasing flow rate. For a flow rate of 30 m/sec we found no sharp rise in wall temperature (such as is characteristic of the transition from the bubble to the film mode of boiling). For a wall temperature of over 300°C we again noted a region with inferior heat transfer. However, when the temperature of the liquid at the entrance into the working tube was increased to 100°C for a flow rate of 16 m/sec, the improvement in heat transfer started being accompanied by the rise in hydraulic resistance, as characteristic of bubble-type boiling. The transition to the film type of heat transfer led to a sharper rise in wall temperature in the case of the hot liquid. It should be noted that, in the experiments with the liquid heated to 100°C, no pressure fluctuations were observed in the region of bubble-type boiling. For "isothermal" flow also no pressure fluctuations were observed in this case. Only on passing to the film type of flow did pressure fluctuations arise at a frequency of 1250-2500 Hz, with a maximum intensity of 30 dB.

We have thus demonstrated experimentally that, even in the case of a precritical pressure, under conditions conducive to the rapid heating of individual moles of relatively cold liquid, severe pressure fluctuations set in, causing the heat-transfer process to acquire certain new characteristic features (the laws governing the change in pressure drop on increasing the heat-transfer intensity differed from those hitherto discussed [6], and the heat-transfer crisis degenerated with increasing w). All this agrees with the proposition that, under certain conditions, thermal motion in the liquid may be one of the sources of the high-frequency pressure fluctuations which exert a substantial influence on transport processes.

## NOTATION

$t_w$, Wall temperature; $t_l$, temperature of the liquid at the inlet into the working tube; $t_s$, saturation temperature at the specified pressure; $t_m$, temperature of maximum specific heat; $T_{cr}$, critical temperature; P, static pressure in the working section; $P_{cr}$, critical pressure; $\Delta P$, pressure drop in the working section; q, specific heat flux, w, rate of flow; d, tube diameter.

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