HEAT TRANSFER IN A PUMPED POLYMETHYLPHENYLSILOXANE LIQUID NEAR THE CRITICAL PRESSURE

Sh. G. Kaplan, K. P. Grinevich,
K. N. Fastova, and R. E. Tolchinskaya

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Experiments indicate that there is improved heat transfer in laminar flow of polymethylphenylsiloxane liquid at pressures near critical.

Experiment indicates [1-4] that heat transfer is greatly accelerated at supercritical pressures with developed turbulence; we have observed a marked improvement in heat transfer at such pressures in laminar flow also.

We used an open loop in which the liquid was driven from the source vessel by gaseous nitrogen; the apparatus has been described [5]. We measured in parallel the parameters characterizing the heat transfer, the hydraulic resistance, and the pressure-oscillation spectrum. We examined the effects on the heat transfer from the flow speed, pipe size, and pressure. We used tubes of Okh18N10T steel of internal diameter from 1.7 to 4.0 mm with heated lengths from 15 to 120 mm and flow speeds from 1.3 to 11.0 m/sec at pressures of 3.43 to $21.6 \cdot 10^5$ N/m^2 ($P/P_{cr} = 0.467$-2.94). The wall temperature was measured at a single point either 7.5 or 20 mm from the inlet to the heated part in the case of the tubes of heated length 15 and 40 mm; in the tube of length 120 mm, we made measurements at 20, 60, and 100 mm. The overall lengths of the tubes were, respectively, 51, 76, and 156 mm. The pressure difference between inlet and outlet was measured by a differential gauge, while the pressure oscillations at the outlet were measured by a piezoelectric transducer. We used PEPMS 2-51 polymethylphenylsiloxane liquid, whose critical parameters ($P_{cr} = 7.35 \cdot 10^5$ N/m^2, $t_{cr} = 502$°C) were obtained by calculation by the method of [6].

Figure 1 shows the heat transfer as a function of flow speed and internal diameter at $9.3 \cdot 10^5$ N/m^2; the temperature at the inlet was 20°C, with a laminar mode of flow, with maximal $Re_d^{in} = 1700$.

Wall temperature in excess of t_{cr} produced considerable increase in heat-transfer rate when there were high-frequency pressure oscillations. Table 1 gives the strength, spectral composition, and related heat-transfer coefficients in relation to flow speed, thermal loading, and tube diameter and length.

The oscillations tended to shift to higher frequencies as the flow speed increased, and the wall temperature at which the heat transfer improved fell somewhat. A high-frequency shift also occurred as the heat flux increased, which again increased the heat-transfer rate. The wall temperature tended to fall as the heat flux increased, and this fall was more pronounced the lower the flow speed, with the heat-transfer rate almost independent of that speed. Any further increase in the thermal loading caused the spectrum to shift: the strongest oscillations shifted toward lower frequencies, which was accompanied by an increased rate of wall-temperature rise. The lower the flow speed, the lower the heat flux at which the oscillations shifted toward the

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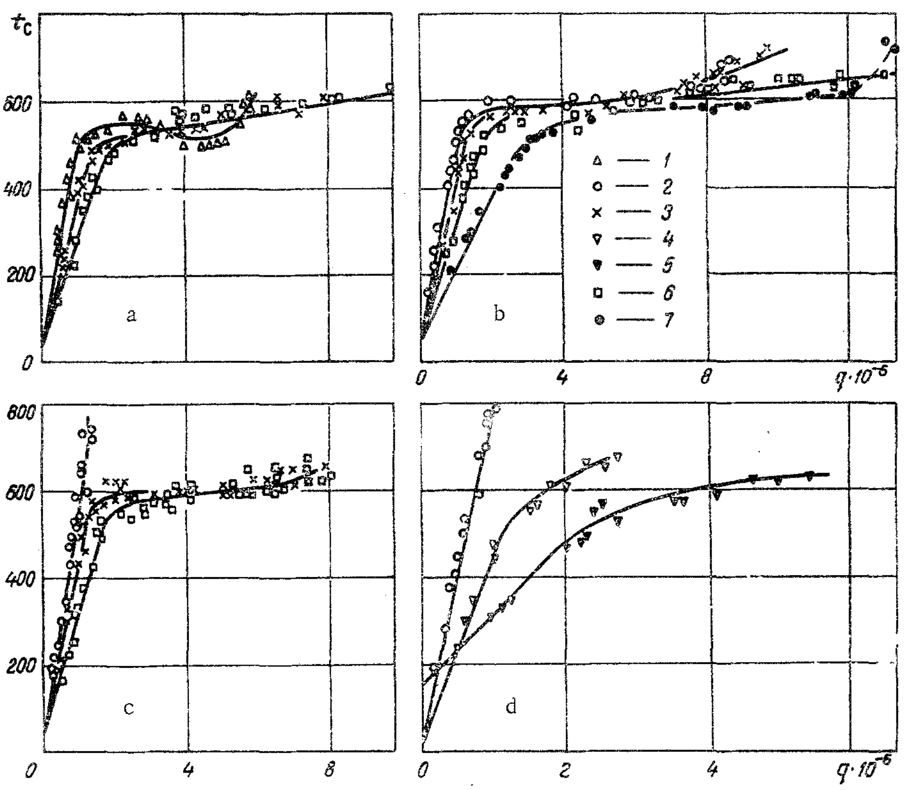

Fig. 1. Effects of flow speed and pipe diameter on heat transfer to PPMS2-51 at P = $9.3 \cdot 10^5$ N/m^2: a) d_{in} = 1.7; b) 2.4; c) 2.8; d) 4.0 mm; a-c) l_{he} = 40; d) 120 mm; 1) w = 1.3; 2) 1.7; 3) 3.2; 4,5) 3.2; 6) 5.3; 7) 11.0 m/sec; 1-4) and 6,7) t_l^{in} = 25.5-150°C.

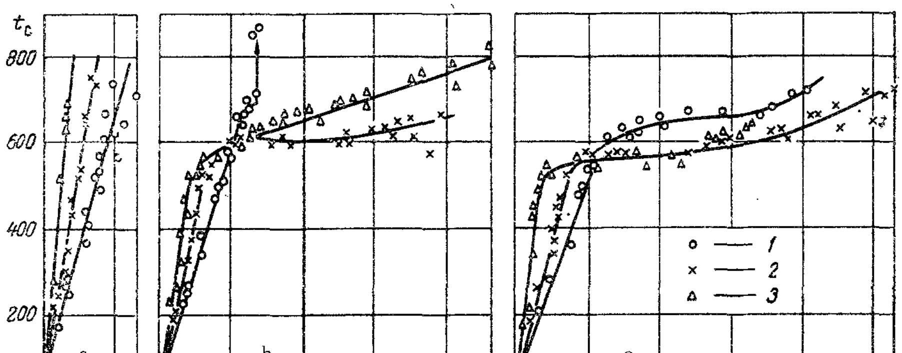

Fig. 2. Effects of heated length on heat transfer at P = $9.3 \cdot 10^5$ N/m^2, t_l^{in} = 25°C: a) w = 1.7 m/sec, d = 2.8 mm; b) w = 3.2 m/sec, d = 2.8 mm; c) w = 3.2 m/sec, d = 2.4 mm; 1) l_{he} = 15; 2) 40; 3) 120 mm.

low-frequency side. The frequency rise and corresponding fall in wall temperature occurred within a certain definite range of heat loads dependent on the working parameters, regardless of whether this state was obtained by raising or reducing the thermal loading.

Improved heat transfer was observed at wall temperatures somewhat less than the critical value in the case of the 11.0 m/sec flow speed. A notable feature here was that weak pressure oscillations arose (200-2560 Hz up to 25 dB) before the heat loading was applied, although the mode of flow was laminar.

TABLE 1. Pressure Variations during Heat Transfer to PPMS2-51

№	d, мм	l, мм	w, м/sec	$P\cdot10^{-5}$, N/м²	t_p, °C		Re_d		Strongest line		
					inlet	outlet	inlet	outlet	$q\cdot10^{-6}$, W/м²	frequency, Hz	strength, dB
1	2	3	4	5	6	7	8	9	10	11	12
1	1,7	40	1,3	9,3	25	210	139	1120	1,2—2,3 2,6—4,8 5,0—5,8	2560, 4060 4060, 6450 1614, 3220, 4060	57, 54 58, 52 57, 54, 56
2	«	«	3,2	«	«	140	342	2170	1,5—2,2 6,4—7,7	2560, 4060 4060, 10240	60, 50 60, 52
3	«	«	5,3	«	«	120	523	2800	1,8—2,2 5,2—5,8 7,0—9,7	2560, 3220, 5130 5120, 10240 4060	60, 53, 54 61, 55 61
4	2,4	15	3,2	«	«	65	450	1000	2,0—2,1 6,6—6,8	4060, 5120, 8130 3220, 4060, 6450, 10240	25, 33, 22 48, 37, 43, 40
5	«	40	1,7	«	«	180	255	1850	2,0—2,4 2,45—8,5	2560, 4060 5120, 10240	60, 53 61, 57
6	2,4	40	3,2	9,3	25	150	480	2900	1,8—2,5 5,8—8,0 8,0—10,0	2560, 4060 8130, 10240 4060	60, 52 56, 58 60

7	«	«	5,3	«	«	115	800	4150	2,0—2,8 7,5—11,0	2560, 3220, 8130 10240	60, 50, 52 58
8	«	«	11,0	«	«	70	1650	4950	3,1—3,3 6,7—8,0 13,0—13,3	4060, 8130 6450 4060	55, 45 62 60
9	«	«	5,3	21,6	«	50	800	1300	2,2—2,6	8130, 10240	25, 28
10	«	«	5,3	«	140	165	4800	5900	3,8—7,8	3220, 4060, 8130	55, 61, 55
11	«	120	3,2	9,3	25	245	450	3800	1,8—2,0 5,8—6,4	3220, 4060, 6450—10240 2560, 800—10240	50, 52, до 40 60, 45 ÷ 55
12	2,8	15	«	«	«	40	535	700	2,1—2,4 >2,4	4060, 8130 vibrations ceased	35, 40
13	«	40	3,2	«	«	100	570	2280	1,2—2,1 6,0—7,0	4060, 6450, 10240 5120, 6450, 10240	37, 40, 35 62, 49, 53
14	2,8	40	5,3	9,3	25	75	940	2540	2,4—2,7 5,8—7,6	5120 8130 4060, 5120, 6450, 10240	48, 40 50, 62, 52, 53
15	«	120	3,2	«	«	255	535	7000	0,9—1,0 8,0—9,0	2560, 4060, 6450 1614, 800—6450	27, 40, 33 60, 5—50
16	«	«	«	13,2	«	«	«	«	1,0—1,45 1,5—2,0 5,0—7,0	80 2560, 3220, 6450 2560, 1280—20480	25 50, 60, 49 61, 50—55
17	4,0	«	4,2	9,3	«	80	1050	3140	2,6—3,0	1600—6450	40—45
18	«	«	«	«	150	215	7300	8800	2,1—2,2 3,4—5,3	4060, 8130 2560, 5120, 8130	55, 42 60, 55, 48

Note. 0 dB has been taken as 1 mV, which corresponds to 353 N/m^2.

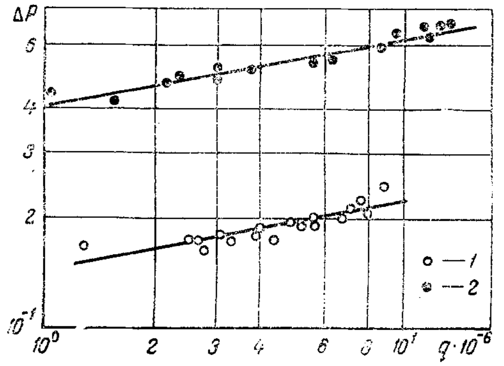

Fig. 3. Pressure difference across working tube as a function of heat flux in the accelerated-transfer state, P = $9.5 \cdot 10^5$ N/m², l_{he} = 120 mm, d_{in} = 2.8 mm, t_l^{in} = 25°C, and w (m/sec) of: 1) 3.2; 2) 6.

High-frequency oscillations became less likely as the tube diameter increased under otherwise equal conditions; the same applied to the onset of improved heat transfer in the laminar state. For instance, increase in diameter from 1.7 to 2.4 mm (l = 40 mm) merely resulted in a certain increase in the wall temperature at which the heat transfer improved, while diameters of 2.8 mm and above resulted in virtually no oscillations at 1.7 m/sec, with no improvement in heat transfer.

In all cases, the outlet temperature rose only slightly at the point where the heat-transfer coefficient improved, and the mode of flow remained laminar ($Re_d^{out} < 2200$).

We examined the effects of the heated length on the transfer at a flow speed of 1.7 m/sec with a tube diameter of 2.8 mm and at w = 3.2 m/sec for tubes of diameter 2.4 and 2.8 mm; Fig. 2 gives the results. Heat transfer in the convective region is accompanied by a wall-temperature distribution characteristic of the laminar state: the temperature rises as the inlet is left behind. The heat-transfer rate rose when the oscillations set in, and the wall temperatures at different points became practically identical. Therefore, Fig. 2 shows results only for the point 100 mm from the inlet for the tube 120 mm long, although the wall temperature was measured at three points. It is clear that no pressure oscillations occurred at w = 1.7 m/sec and d = 2.8 mm no matter what the working length, with no improvement in heat transfer; pressure oscillations set in as the flow speed increased, and the strength of the oscillations increased with the tube length. For instance, with w = 3.2 m/sec and d = 2.8 mm with a tube having l_{he} = 15 mm the low-intensity pressure oscillations arose at t_w = 650°C, with some corresponding improvement in the heat transfer; however, at q = $2.6 \cdot 10^6$ w/m² the oscillations ceased, and the wall temperature rose sharply to 870°C. Increase in working length to 40 or 120 mm caused the heat transfer to intensify for t_h > 520°C, which was accompanied by high-frequency pressure oscillations, whose intensity increased with the heat loading. We found improved-transfer modes with a tube having d = 2.4 mm and w = 3.2 m/sec at all lengths, but the improvement for the 15-mm length occurred at higher wall temperatures. The pressure oscillations were also less strong than those with 40 and 120 mm tubes.

The pressure difference as a function of heat flux is shown in Fig. 3 for l_{he} = 120 mm; the increase in transfer rate is accompanied by a slight increase in hydraulic resistance ($\Delta P \sim q^{0.2}$).

We examined the effects of pressure on the heat transfer for tubes 2.8 × 3.5 × 120 mm and 2.4 × 3.0 × 40 mm; Fig.4 shows that the heat transfer varied from the pressure at 3.2 m/sec as follows. A subcritical pressure of $3.43 \cdot 10^5$ N/m² produced improved heat transfer at wall temperatures close to the saturation point, due to bubble boiling; the increased heat-transfer rate was not accompanied by pressure oscillations. On increasing the loading to $1.15 \cdot 10^6$ W/m², the wall temperature rose sharply, which is characteristic of the transition from bubble boiling to film boiling.

At a transcritical pressure ($7.35 \cdot 10^5$ N/m²) there was a change in the mode of heat transfer; at wall temperatures above 510°C the transfer was accompanied by a broad spectrum of acoustic oscillations. The strength of these increased with the heat loading, and the heat-transfer coefficient increased correspondingly. The maximum heat flux exceeded by a factor 8 the critical heat flux at $3.43 \cdot 10^5$ N/m², and no marked rise in wall temperature corresponding to a heat-transfer crisis was observed.

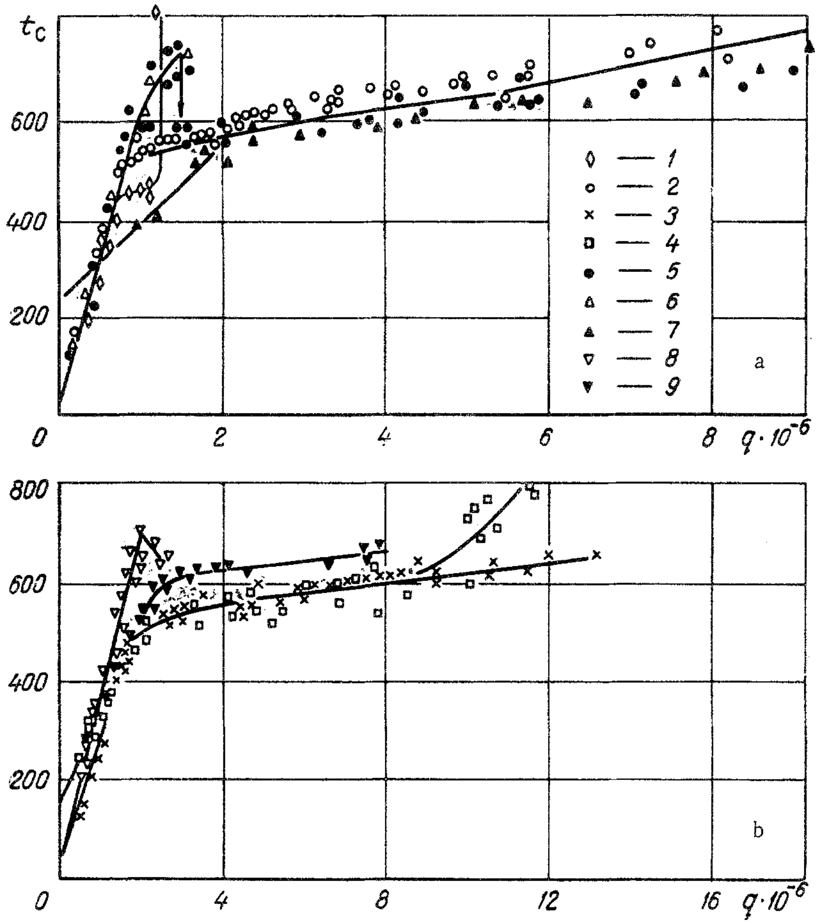

Fig. 4. Effects of pressure on heat transfer: a) d = 2.8 mm; l_{he} = 120 mm, w = 3.2 m/sec; b) d = 2.4 mm, l_{he} = 40 mm, w = 5.3 m/sec; 1) p = $3.4 \cdot 10^5$ N/m^2; 2) $7.35 \cdot 10^5$; 3,4) $9.3 \cdot 10^5$; 5) $13.2 \cdot 10^5$; 6,7) $17.2 \cdot 10^5$; 8,9) $21.6 \cdot 10^5$ N/m^2; in 1-3, 5, 6, 8) t_l^{in} = 25; 4,9) 140; 7) 240°C.

At $13.2 \cdot 10^5$ N/m^2, raising the wall temperature of 750°C (q = $1.35 \cdot 10^6$–$1.45 \cdot 10^6$ W/m^2) did not produce strong oscillations, and the heat-transfer factor was not substantially altered. Any further increase in heat loading produced strong oscillations, with a stepwise reduction in wall temperature by about 200°C, with onset of improved heat transfer. The strongest oscillations occurred at 3220 and 2560 Hz. At $17.0 \cdot 10^5$ N/m^2, there were no oscillations, although the wall temperature rose to 850°C, and there was also no change in heat transfer.

We used tubes of internal diameter 2.4 mm at pressures of 9.3 and $21.6 \cdot 10^5$ N/m^2 and 5.3 m/sec; Fig. 4b shows that at $9.3 \cdot 10^5$ N/m^2 we get for $t_w > 520$°C a considerable increase in heat-transfer rate, which is accompanied by pressure oscillations. At $21.6 \cdot 10^5$ N/m^2, the heat transfer in the laminar state was not accompanied by oscillation on raising the wall temperature to 700°C, but any further increase in heat loading produced weak oscillations, with a slight improvement in heat transfer.

We examined the effects of flow mode on the improved heat transfer using a turbulent flow; the flow mode was varied at a constant flow speed by increasing the liquid inlet temperature. For comparison we chose tests in which the laminar flow produced only slightly improved heat transfer (Figs. 1d and 4). Turbulent flow at $t_w > 520$°C showed increasing oscillation intensity and improved heat transfer, i.e., the transfer from the laminar to the turbulent flow mode favored the production of high-frequency oscillations and increased the heat-transfer rate.

PPMS2-51 has a low critical pressure and some other valuable properties (high resistance to chemical damage, radiation damage, and pyrolysis, as well as high ignition temperature, a low melting point, good dielectric properties, and a high boiling point); it is therefore a good heat carrier that can take high heat fluxes with low energy consumption to increase the heat transfer rate.

NOTATION

t_w is the wall temperature; t_{cr} is the critical temperature; t_l is the liquid temperature; P is the working pressure; P_{cr} is the critical pressure; ΔP is the pressure drop across working tube; d is the channel diameter; l_{he} is the heated length; w is the flow velocity; q is the heat flux; Re_d is the Reynolds number.

LITERATURE CITED

1. R. G. Deissler, Trans. ASME, 76, No. 1 (1954).
2. Haynes and Wolf, ARS, [Russian translation], No. 2 (1962).
3. N. L. Kafengauz, Dokl. Akad. Nauk SSSR, 173, No. 3 (1967).
4. Sh. G. Kaplan and R. E. Tolchinskaya, Inzh.-Fiz. Zh., 21, No. 2 (1971).
5. Sh. G. Kaplan and R. E. Tolchinskaya, Inzh.-Fiz. Zh., 17, No. 3 (1969).
6. S. Bretsznajder, Prediction of Transport and Other Physical Properties of Fluids [Russian translation], Moscow-Leningrad (1966).