FREE CONVECTIVE HEAT EXCHANGE WITH SULFUR HEXAFLUORIDE IN THE SUPERCRITICAL REGION

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Experimental data are presented on the heat transfer coefficient of platinum wire with sulfur hexafluoride in the supercritical region. The heat transfer coefficient increases by severalfold and passes through a maximum on the isotherms near the critical isotherm with a temperature head of 0.5°.

As is well known, near the liquid – vapor critical point heat transfer takes place with sharply varying properties of the matter. A large number of studies (not cited here) have been made of the influence of the singularities in the behavior of the matter on the heat transfer in this region.

In the following we examine heat exchange with sulfur hexafluoride in the supercritical region. In its chemical properties SF_6 is close to the inert gases and has high electric strength. According to [1] the critical parameters of SF_6 are $t_* = 45.56°$ C, $p_* = 37.6$ bar.

In the tests we used the experimental setup described in [2]. A 29-μ-diam. platinum filament running along the axis of vertically and horizontally positioned cylindrical channels serves as the heater and resistance thermometer. The chamber filled with SF_6 was placed in a thermostat whose temperature was maintained to within $\pm 0.01°$ C. Prior to filling, the impurities were removed from the SF_6 using the freezeout technique.

We investigated the behavior of the heat transfer coefficient α as a function of the pressure p for the constant temperature head $\Delta t = 0.5°$ along the isotherms.

Figure 1 shows the six isotherms 1, 2, 3, 4, 5, 6, corresponding to the temperatures 46.05, 47.20, 48.20, 50.20, 54.00, 60.00° C, obtained as a result of experiments with a horizontal filament. The series of isotherms for the vertical filament was recorded at the temperatures 46.05, 48.20, 50.20, 54.00 and 60.00°C.

The dependence of the heat transfer coefficient α on the temperature head along the isobars is shown in Fig. 2, where curves 1, 3, 5 are experiments with horizontal filaments, curves 2, 4, 6 are experiments with vertical filaments; for curves 3, 4 p = 40.5, t = 48.20°; for curves 5, 6 p = 38.0 bar, t = 46.05° C.

We see from Fig. 1 that the heat transfer coefficient passes through a maximum. The more the chamber temperature exceeds the critical temperature, the lower this maximum is and the higher the pressures at which it is observed. On the 46.05° C, isotherm, i.e., 0.5° above the critical temperature, the quantity α exceeds by eight times the value which the heat transfer coefficient would have for gradual and monotonic variation with the pressure. At a distance of 15° from the critical temperature the value of α in this comparison differs only by a factor of 1.5.

For the vertical wire the dependence of α on the pressure and temperature is the same as for the horizontal wire, but the corresponding maximal values are about 20% lower. The maximal values of the heat transfer coefficient for the horizontal and vertical filaments are presented in Table 1.

In the coordinates p–t the line of α maxima corresponds to continuation past the critical point of the liquid–vapor coexistence curve [3]. A maximum of the heat transfer coefficient can also be observed with isobaric variation of the state of the material. The experiments were made with variable temperature head along the isobars. The dependence of α on Δt was determined for constant pressure. It was found that the choice of the pressure has a significant effect in this case. Thus, for the pressure p*, corresponding to the maximum of α on the curve α (p) for a given chamber temperature, the heat transfer coefficient

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TABLE 1

t, °C	$\tau = \frac{T}{T_*}$	P^*, bar		$\alpha^* \cdot 10^{-3}$ W · m^{-2} · deg^{-1}	
		hor.	vert.	hor.	vert.
46.05	1.001	38.6	38.6	8.0	6.2
46.35	1.002	38.8	—	7.4	—
47.20	1.005	39.5	—	6.6	—
48.20	1.008	40.3	40.4	5.2	3.9
50.20	1.014	42.1	42.1	4.3	3.2
54.00	1.026	45.8	45.9	2.9	2.5
60.00	1.045	51.3	50.9	2.4	2.0

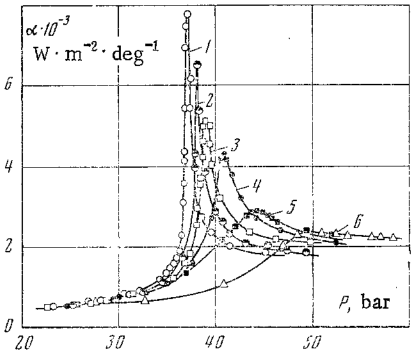

Fig. 1

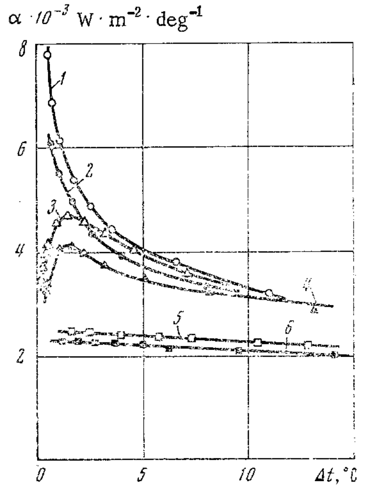

Fig. 2

decreases sharply with increase of Δt (curves 1 and 2 in Fig. 2). If the pressure exceeds p^* slightly there is a marked maximum on the α (Δt) curve (curves 3 and 4 in Fig. 2). For a lower pressure $p < p^*$, α varies only slightly with increase of Δt (curves 5 and 6 in Fig. 2). The critical dependence for free convection, as is known, has the form $N = C(R)^n$. Here N is the Nusselt number, R is the Rayleigh number, G is the Grashof number, P is the Prandtl number, C and n are empirical coefficients

$$R = GP = \frac{g\beta l^3 \rho^2 c_p \Delta t}{\eta\lambda}$$

We see from this relation that the heat transfer coefficient is proportional to the specific heat and the thermal expansion coefficient β. It is the extremal behavior of c_p and β for supercritical transitions which causes the increase of the free convective heat transfer. Strong turbulent convection near the critical point was observed in the SF_6 visually and was photographed. The convective flux patterns are similar to the photographs obtained in [4].

The marked decrease of α on the isobars (curves 1, 2, in Fig. 2) is a result of the fact that with increase of Δt there is an increase of the defining temperature to which the values of β and c_p are to be referred. At this temperature they are already on the descending branch of the isobar [5].

For the criterial analysis of the experimental results on heat transfer in SF_6 near the critical point it is necessary to have information on the thermophysical properties. Since such data are not yet available, the calculation using similarity theory was conducted only far from the critical point. We also examined the conditions under which convection arises in SF_6 in the given setup.

In the present case the process in question can be considered as heat transfer in the gap between coaxial cylinders. Therefore we take as the governing dimension l the channel radius, equal to 2 cm. For the cylinder diameter ratio D/d = 1380 the criterial analysis can be performed in this fashion only for low pressures. For pressures of 1 bar and lower SF_6 can be considered an ideal gas. To calculate the properties we can use the equations which are valid for an ideal gas. We took the arithmetic average temperature across the gap as the defining temperature. The thermal conductivity is calculated from the formula for spherical, nonpolar molecules using the Lennard−Jones potential [6]

$$\lambda 10^7 = 1989 \frac{\sqrt{T/M}}{\sigma^2 \Omega^{(2.2)*}(T^*)} \left(\frac{4}{15}\frac{c_v}{R^*} + \frac{3}{5}\right) \frac{\text{kcal}}{\text{cm} \cdot \text{sec} \cdot {}^\circ\text{K}}$$

To determine the convection coefficient ε_*, equal to λ_{eff}/λ, it is necessary to find the effective thermal conductivity λ_{eff}. In the case in which all the heat in the gap between the cylinders is transferred only by thermal conduction, we have for the heat flux

TABLE 2

p, mm Hg	Δt, °C	Q_e 10^{-3}, W	Q 10^{-3}, W	ε_*	lg ε_*	R	lg R
Vertical filament							
755	8.7	11.8	9.05	1.30	0.11	$3.6\cdot10^5$	5.56
	23.4	34.5	25.7	1.34	0.13	$8.3\cdot10^5$	5.92
	44.7	71.7	51.9	1.38	0.14	$13.7\cdot10^5$	6.14
202.5	9.9	11.8	10.5	1.13	0.05	$2.8\cdot10^4$	4.45
	26.7	34.6	29.5	1.17	0.07	$8.7\cdot10^4$	4.94
	50.8	71.7	60.4	1.19	0.08	$10.6\cdot10^4$	5.03
123	10.3	11.7	10.9	1.07	0.03	$1.08\cdot10^4$	4.03
	27.8	34.6	30.5	1.12	0.05	$2.56\cdot10^4$	4.40
	52.9	71.6	62.9	1.14	0.06	$4.03\cdot10^4$	4.60
63.0	10.7	11.7	11.4	1.03	0.02	$2.9\cdot10^3$	3.50
	29.6	34.6	33.0	1.05	0.02	$7.0\cdot10^3$	3.80
	56.3	72.0	67.4	1.07	0.03	$11.1\cdot10^3$	4.04
32.0	10.9	11.7	11.65	1.006	0.00	$0.8\cdot10^3$	2.90
	30.8	34.6	34.5	1.00	0.00	$1.9\cdot10^3$	3.28
	59.4	72.0	71.9	1.00	0.00	$2.9\cdot10^3$	3.46
Horizontal filament							
755	12.5	21.2	13.1	1.62	0.21	$3.2\cdot10^5$	5.50
	26.7	49.7	28.8	1.72	0.24	$9.5\cdot10^5$	5.98
	35.8	69.5	39.1	1.78	0.25	$12.0\cdot10^5$	6.08
203.0	15.0	21.3	15.9	1.34	0.13	$4.10\cdot10^4$	4.61
	32.3	50.2	36.7	1.37	0.15	$7.8\cdot10^4$	4.90
	42.2	68.3	48.4	1.41	0.15	$9.2\cdot10^4$	4.96
123	16.1	21.2	17.0	1.25	0.10	$1.60\cdot10^4$	4.21
	34.5	50.2	38.6	1.30	0.11	$3.00\cdot10^4$	4.48
	45.0	68.7	51.9	1.32	0.12	$3.63\cdot10^4$	4.60
63	18.00	21.7	19.3	1.11	0.05	$1.28\cdot10^3$	3.70
	38.0	51.5	43.9	1.17	0.07	$2.4\cdot10^3$	3.90
	50.0	71.6	65.0	1.20	0.08	$2.8\cdot10^3$	4.00
32	10.9	11.7	11.4	1.02	0.012	$0.77\cdot10^3$	2.89
	29.8	34.2	33.0	1.04	0.015	$1.82\cdot10^3$	3.26
	42.4	50.9	48.7	1.05	0.021	$2.35\cdot10^3$	3.37

$$Q=\frac{2\pi L\lambda\Delta t}{\ln(D/d)}.$$

By analogy with this expression, for the convection case we have

$$Q_e=\frac{2\pi L\lambda_{eff}\Delta t}{\ln(D/d)}$$

Consequently, $\lambda_{eff}=\lambda Q_e/Q$. The heat flux Q_e and the temperature head Δt are determined from experiments, the other quantities will be parameters of the setup.

The experimental values of the convection coefficients, and also the values of the Rayleigh number R in SF_6 at atmospheric and lower pressures and t = 26° C are shown in Table 2. Several conclusions can be drawn from the tabulated results. For the given setup parameters, convection in SF_6 exists to a pressure of 30 mm Hg. Convection begins to become noticeable for Rayleigh numbers $R \geq 1000$, which is in agreement with the estimates of this quantity by other authors [7, 8].

For the same pressure and temperature head the convection coefficient for the vertical filament is lower than for the horizontal filament. The curves of log ε_* (log R) obtained do not agree with the Mikheev–Kraussold curve, lying considerably below the latter. A similar result has been obtained in other studies [9] and also by R. V. Shingarev in his candidate dissertation.

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