HEAT TRANSFER FROM A CYLINDRICAL HEATER TO SOLIDIFIED REFRIGERANTS

F. M. Pozvonkov, A. N. Selivanov, and L. L. Vasil'ev UDC 536.21

The results of an experimental investigation of the equivalent thermal conductivity of the gas layer forming around a cylindrical heater placed in a solidified gas (argon or nitrogen) at pressures $P \leq 3$ mm Hg are given for thermal fluxes of up to 50 W/m^2.

For calculating cryostatic devices where solidified gases are used as refrigerants, it is important to know the regularities of heat exchange between the heat-releasing elements and sublimating solid-phase refrigerants.

We have investigated experimentally the heat transfer from a cylindrical heater to solidified argon and nitrogen.

The experiments were performed in a cryostat consisting of an inner and an outer Dewar vessel, sealed hermetically with a lid. Liquid nitrogen was poured into the outer, protective vessel. Solidified gas in the inner vessel was produced by filling the vessel with the liquid refrigerant and then pumping out the vapor.

The heat-releasing element consisted of a heater–thermometer, made in the shape of a hollow copper cylinder with a height of 60 mm, a diameter of 30 mm, and a wall thickness of 0.1 mm, which carried a winding of 0.1-mm copper wire with the turns wound next to each other. The winding was coated with varnish on top. The heater was placed in the vertical position, coaxially with the Dewar vessel.

The experiments were performed with the clearances forming as a result of sublimation of the refrigerant around the heater both closed and open. In the first case, the heater was completely surrounded by the solidified refrigerant. In the second case, the refrigerant above the upper edge of the heater was first removed by means of a flat heater, so that the gas layer around the heater communicated with the gas volume in the cryostat.

The temperatures of the solid phase and the heater and the temperature difference between the heater and the solidified refrigerant were measured in the experiments. The temperature profile in the gas layer around the heater was measured by means of copper–Constantan microthermocouples with a diameter of 0.08 mm, which were positioned parallel to the generatrices of the heater cylinder. The thermocouple junctions were located at mid-height of the heater. The error in measuring the temperature difference was equal to $\pm (0.005\text{-}0.1°K)$.

The gas pressure was determined with respect to the saturation temperature, measured at the point where the thermocouple emerges from the solid phase and enters the gas layer.

The experiments were performed for thermal fluxes $q = 3\text{-}45$ W/m^2 at pressures $P = 5\text{-}430$ mm Hg for argon and $P = 5\text{-}75$ mm Hg for nitrogen. The porosity of argon amounted to 27%, while the porosity of nitrogen was equal to 19%.

The heater power was kept constant with an accuracy of ±1.0%.

The equivalent thermal-conductivity coefficient and the gas-layer thickness under the conditions q = idem and P = idem for a closed clearance were determined by means of the expressions derived for an infinite-length plate without an allowance for its heat capacity [1]:

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$$\lambda_{eq} = \frac{qH}{\Delta T\pi} \ln \sqrt{1 + \frac{2\pi q\tau}{Hr_0\rho_0}} \quad (1)$$

and

$$h = \frac{H}{\pi}\left(\sqrt{1 + \frac{2\pi q\tau}{Hr_0\rho_0}} - 1\right). \quad (2)$$

For an open clearance, the values of λ_{eq} and h were calculated by means of expressions derived under conditions similar to those of (1) and (2):

$$\lambda_{eq} = \frac{q}{\Delta T}\frac{2H}{\pi} \ln \sqrt{1 + \frac{\pi}{H}\frac{q\tau}{r_0\rho_0}} \quad (3)$$

and

$$h = \frac{2H}{\pi}\left(\sqrt{1 + \frac{\pi}{H}\frac{q\tau}{r_0\rho_0}} - 1\right). \quad (4)$$

The experimental values of λ_{eq} were reduced to the values of the thermal-conductivity coefficient λ_t under viscous conditions, calculated by means of Sutherland's equation [2] for the mean temperature in the gas layer.

Figure 1 shows the experimental dependences of λ_{eq}/λ_t on the clearance width under different sets of conditions.

Analysis of the experimental results shows that there are various types of heat transfer under conditions of refrigerant sublimation in a vacuum.

I. For Knudsen numbers in the range $0.01 < Kn < 1$ and $q \leqslant 25$ W/m^2, the experimental data are described fairly adequately by the equation

$$\frac{\lambda_{eq}}{\lambda_t} = \frac{1}{1 + 2\beta\,\mathrm{Kn}}. \quad (5)$$

Figure 2 shows the results of the processing of experimental data for argon and nitrogen by means of Eq. (5) in a λ_{eq}/λ_t vs 1/Kn plot. The accommodation coefficient obtained on the basis of data from Fig. 2 is equal to $\beta = 3.2$, which corresponds to the accommodation coefficient values $\alpha = 0.74$ for argon and $\alpha = 0.66$ for nitrogen in the heater–solidified gas system.

Thus, it can be assumed that, in our case ($q = 3$-25 W/m^2; $0.01 < Kn < 1$), heat transfer through the gas layer takes place under the viscous-molecular conditions of λ.

For the thermal flux $q = 45$ W/m^2, an unsteady process (pressure variation) was observed for some time after current was supplied to the heater circuit. Therefore, it was difficult to draw conclusions concerning the regularities of heat exchange in narrow slots ($h < 0.5$ mm) under such conditions.

II. The heat-exchange intensity at Knudsen numbers $Kn < 0.01$ exceeds the heat-exchange intensity under viscous conditions by up to 50% (up to the development of free convection). The intensification of heat transfer is explained by the development of currents during sublimation of the solid phase. The possibility of such currents arising during the sublimation of frozen liquids in a vacuum has been proven theoretically [5] and experimentally [6]. A direct indication of the existence of discrete currents or streams was that the readings of certain thermocouples at the passage from the solid phase to the gas layer displayed a nonstationary pulsating character during the experiments.

A qualitative explanation of the experimental results for $Kn < 0.01$ can be given by using the following heat-exchange model (Fig. 3).

Generally, the gas layer surrounding the heater can be divided into two zones: a gas layer with the thickness h_t, which is agitated by gas currents, and the viscous gas layer h_v adjacent to the heater. Heat transfer is effected by forced convection through the first zone and by heat conductivity under viscous conditions through the second zone.

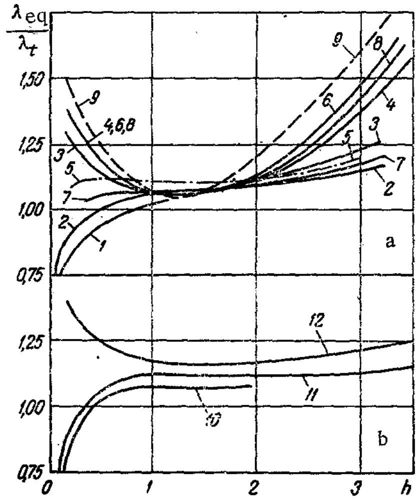

Fig. 1

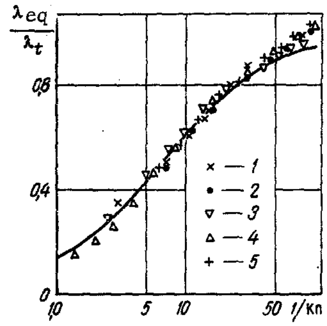

Fig. 2

Fig. 1. Dependence of λ_{eq}/λ_t on the gas-layer thickness under sublimation conditions. a) Solidified argon (Π = 27%) in an open clearance: 1) P = 4 mm Hg, q = 7 W/m^2; 2) P = 5; 3) 90; 4) 300 at q = 25; 5) P = 7; 6) 310 at q = 45; in a closed clearance: 7) P = 11; 8) 290; 9) P = 430 at q = 45; b) solidified nitrogen (Π = 19%) in an open clearance: 10) P = 7 mm Hg, q = 3 W/m^2; 11) 5 and 25; 12) 66 and 46. The values of h are given in mm.

Fig. 2. Ratio λ_{eq}/λ_t as a function of the Knudsen number for sublimating solidified argon. 1) P = 4 mm Hg, q = 7 W/m^2, Π = 27%; 2) 5, 25, and 27%, respectively; 3) 7, 3, and 12%; sublimating solidified nitrogen: 4) P = 3, q = 3, and Π = 8%; 5) 5, 25, and 19%; the solid curve was calculated by means of expression (5) for β = 3.2.

The equivalent thermal-conductivity coefficient for this model is written in the following form:

$$\lambda_{eq} = \frac{h}{\dfrac{h_v}{\lambda_v} + \dfrac{h_s}{\lambda_s}} \qquad (6)$$

or, approximately ($\lambda_v = \lambda_t$),

$$\frac{\lambda_{eq}}{\lambda_t} = \frac{1}{1 - \dfrac{h_s}{h}\left(1 - \dfrac{\lambda_t}{\lambda_s}\right)}. \qquad (7)$$

If we assume that the equivalent thermal conductivity of the gas is constant within the turbulent or stream zone (q = idem, P = idem), the proposed model is supported qualitatively by experimental data.

In experiments with argon at P = 5 mm Hg, the value of λ_{eq}/λ_t remains approximately constant as the clearance width varies; it is equal to λ_{eq}/λ_t = 1.13 for q = 45 W/m^2 and λ_{eq}/λ_t = 1.08 for q = 25 W/m^2. The behavior of the temperature profile in the clearance (Fig. 3a) suggests that there are streams along the entire thickness of the gas layer. The somewhat higher value of λ_{eq}/λ_t at h > 2 mm is explained by an increase in radiative heat transfer.

With an increase in pressure in the gas layer, the length of streams and, consequently, the turbulent-layer thickness, decrease [6], so that the latter amounts to only a fraction of the gas-layer thickness. In this case, in correspondence with (7), the value of λ_{eq}/λ_t decreases as the gas-layer thickness increases.

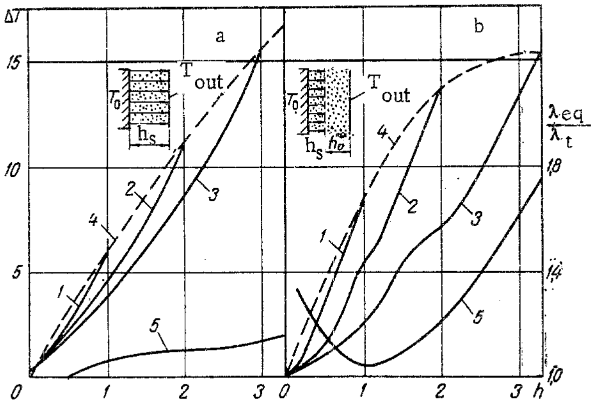

Fig. 3

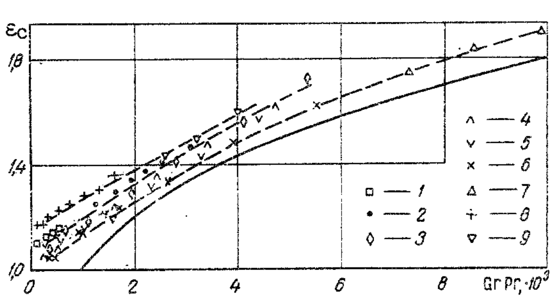

Fig. 4

Fig. 3. Temperature profiles in clearances with different widths (1, 2, and 3) and dependences of the temperature difference between the heater and solidified argon (4) and of λ_{eq}/λ_t (5) on the clearance width; a) q = 25 W/m^2, P = 5 mm Hg; b) q = 45 W/m^2, P = 430 mm Hg. The values of ΔT are given in degrees Kelvin and the values of h in mm.

Fig. 4. Convection coefficient as a function of the gas-layer thickness for sublimating solidified argon (Π = 27%) in an open clearance: 1) P = 90 mm Hg, q = 25 W/m^2; 2) 195 and 25, respectively; 3) 300 and 25, respectively; 4) 310 and 45, respectively; in a closed clearance: 5) P = 290, q = 45; 6) 430 and 45, respectively; 7) 430 and 60, respectively; sublimation of solidified nitrogen (Π = 19%) in a closed clearance: 8) P = 66 mm Hg; q = 45 W/m^2; 9) 75 and 60, respectively. The solid curve is based on expression (8).

Thus, for argon at P = 430 mm Hg and q = 25 W/m^2, the ratio λ_{eq}/λ_t decreases from 1.4 to 1.04 as the gas-layer thickness increases from 0.2 to 1.2 mm (Fig. 1).

Figure 3a and b illustrates the difference in the behavior of the temperature profiles in the clearance for the case where currents are present throughout the gas layer and the case where only a part of the gas layer is turbulent. It is evident that the effect of the thermal flux and the pressure on the heat exchange in sublimation (Kn < 0.01) is connected with the effect of these parameters on stream sublimation, so that a special and thorough study of the sublimation process is necessary for a rigorous description of the heat-exchange process.

Experiments have shown that, before free convection develops in the clearance, the difference between the values of λ_{eq} (P = idem, q = idem) for closed and open clearances lies within the limits of the experimental error ($\delta\lambda_{eq}$ = 2-3%).

III. Free convection developed in the gas layer for Rayleigh number values Ra = GrPr = 300-600.

Figure 4 shows the dependences of the convection coefficient $\varepsilon_c = \lambda_{eq}/\lambda_t$ on the Ra number obtained in our experiments and the dependence for free convection in slots [8],

$$\varepsilon_c = 0.18\,(\mathrm{Gr\,Pr})^{0.25}. \tag{8}$$

The physical parameters of the gas were determined for the mean temperature of the gas layer. The gas-layer thickness h was used as the determining dimension.

The data given in Fig. 4 indicate that, under sublimation conditions, free convection occurs for smaller values of the Ra number than under ordinary conditions, while the heat transfer in an open clearance is more intensive than in a closed one.

In the range Ra = 10^3 - $1.5 \cdot 10^4$, the convection coefficient for sublimation of solidified argon (Π = 27%) exceeds the coefficient of convection under ordinary conditions by 3-12% for a closed clearance and by 7-15% for an open clearance; for sublimation of solidified nitrogen (Π = 19%), this coefficient exceeds the normal convection coefficient by 10-20% for a closed clearance.

The experimental curves 2 and 3 in Fig. 3b show the temperature distribution in the clearance under free convection conditions. It is evident that, as in the absence of convection, the profile of temperatures at the sublimating surface reflects the effect of turbulence in the boundary layer of the gas.

It can be assumed that turbulence in the gas layer at the sublimating surface is the cause of intensification of heat transfer through the gas layer. At the same time, the porous refrigerant layer above the clearance causes hydraulic resistance, which affects the gasdynamics of free convection in closed clearances.

Thus, we have established the basic regularities of heat transfer through a clearance from a cylindrical heater to solidified argon or nitrogen for thermal fluxes of 3-45 W/m^2 at pressures $P \leqslant 3$ mm Hg:

a) For Knudsen numbers in the range $0.01 < Kn < 1$ and $q \leqslant 30$ W/m^2, heat transfer is effected by thermal conductivity under viscous-molecular conditions;

b) the intensity of heat transfer at $Kn < 0.01$ exceeds by 5-50% the intensity under viscous conditions of thermal conductivity, which is connected with the effect of stream sublimation; the proposed model explains qualitatively the behavior of λ_{eg}/λ_t with changes in the clearance width;

c) free convection develops in the gas layer for Rayleigh numbers in the range $Ra = GrPr = 300\text{-}600$.

It has been found that the value of λ_{eq}/λ_t for $Ra = 10^3\text{-}1.5 \cdot 10^4$ exceeds that for ordinary free convection in the clearance by 20%; the intensity of heat transfer in open clearances is higher than in closed clearances.

NOTATION

q, thermal flux; ΔT, temperature difference between the heater and the sublimating wall surface; P, pressure; τ, time; H, heater height; h, gas-layer thickness; ρ_0 and r_0, density and sublimation heat of the solidified refrigerant, respectively; l, mean free path of molecules; h_v and λ_v, thickness and thermal conductivity of the viscous gas layer, respectively; h_s and λ_s, thickness and effective thermal conductivity of the turbulent or stream gas layer, respectively; Kn, Knudsen number ($Kn = l/h$); Gr, Grashof number; Pr, Prandtl number.

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