STUDY OF HEAT TRANSFER IN THE GAS-COOLED NECKS OF HELIUM VESSELS AND CRYOSTATS

N. V. Markelova and M. G. Kaganer

UDC 536.25

A method of calculating heat flow along helium-cooled necks is refined on the basis of an experimental study.

Helium cryostats and vessels with a wide neck have come into increasingly broad use in recent years to cool superconducting devices and other equipment requiring very low temperatures for operation. In these devices, heat flows to the liquid helium mainly along the wall of the neck and the gas filling the neck. Several studies [1-4] have examined this subject but are theoretical in nature and have not been experimentally substantiated.

This article uses an experimental helium cryostat (Fig. 1) to measure heat flow along a neck cooled by gaseous helium. The test element took the form of an inset 1 in the shape of a hollow cylinder made of steel Kh18N10T. The cylinder was 200 mm in diameter, 830 mm in height, and 0.8 mm in wall thickness. The measurements of heat flow along the neck of the insert were made more accurate by shielding the insert from protective chamber 2 with liquid helium and shielding it from protective chamber 4 with liquid nitrogen. Helium chamber 2 was in turn shielded from the flow of heat to the lateral surface of protective chamber 3 with liquid nitrogen.

The protective helium chamber (capacity 18 liters), in the form of a hollow cylinder, was secured to the nitrogen bath by means of four glass-plastic suspension pieces. The nitrogen bath 4 (capacity 4 liters), which served to eliminate heat flow by radiation from the warm cover, had sufficiently good heat exchange with the inside surface of the insert thanks to a sliding contact. The bath was attached to the cover by means of a pipe allowing nitrogen vapors to escape and a mushroom-shaped seal. The seal permitted heightwise movement of the bath.

The outer surfaces of the helium 2 and nitrogen 4 protective baths and the insert 1 were covered with an aluminum coating to reduce radiative heat flow.

The tests were conducted at warm boundary surface temperatures of 77-220°K and ratios L/D from 1.5 to 3.5. Heat flux was determined from the rate of vaporization of the liquid helium by means of a GSB-400 counter with an error of 1.5%; here, we took into account the part of the gas left in the vessel. The temperature of the wall and cover was measured with 0.15-mm-diam. absolute Manganin–Constantan thermocouples and an R-306 potentiometer.

We also conducted tests on serially produced helium cryostat KG-60/300, with a capacity of 60 liters and a neck diameter of 300 mm [5].

It was established earlier [6] that there is additional heat flow in the necks of nitrogen cryostats due to free convection in the gas column. It is difficult to directly determine heat flow to the liquid by free convection in tests with liquid helium because most of it (85-90%) is removed by vaporizing helium; on the other hand, free convection plays an important role in heat exchange between the gas and the walls of the neck in the case of helium. The test data obtained in this article on heat flow to liquid helium was used to determine the Nu numbers characterizing this heat transfer.

The following equation was obtained in [7] for the dependence of the Nusselt number on the modified Rayleigh number Ra* for a cylinder open at both ends in the case of a constant heat flow on the lateral surface:

All-Union Scientific-Research Institute of Helium Technology, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 47, No. 5, pp. 749-753, November, 1984. Original article submitted February 22, 1983.

0022-0841/84/4705-1288$08.50

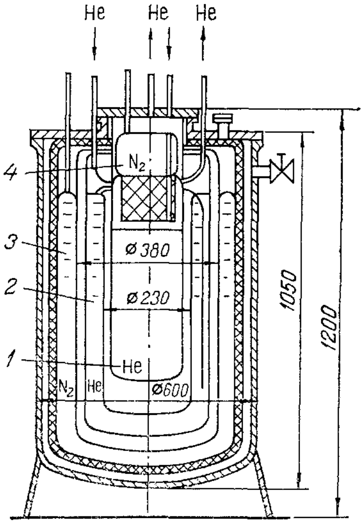

Fig. 1. Basic diagram of experimental helium cryostat.

$$\mathrm{Nu}=0.55\left(\mathrm{Ra}^*\frac{L}{D}\right)^{0.20}. \tag{1}$$

The determining geometric dimension in the Ra* number is the diameter. The temperature difference between the wall and the gas is considered by means of the multiplier qL/λ_g, and the ratio L/D takes into account the effect of height in the limited volume of the neck.

In the necks of helium vessels and cryostats, heat flow from the wall to the gas decreases from the warm to the cold end. There is a similar change in λ_g, and the ratio q/λ_g may be assumed approximately constant.

In determining Ra*, we calculated the unit heat flow from the wall to the gas from the equation $q = mC_p\Delta T/f$. The values of the physical quantities were taken at the arithmetic mean temperature of the wall.

By analogy with Eq. (1), the equation obtained earlier $\varepsilon_k = f(\mathrm{Ra})$ for broad necks cooled by nitrogen vapors was converted to a function of the modified number Ra* (Fig. 2). It is described by the equation

$$\varepsilon_k = 0.0141\left(\mathrm{Ra}^*\frac{L}{D}\right)^{0.240}. \tag{2}$$

Figure 2 also shows two values determined in tests on helium.

We also studied radiative heat transfer. It was evaluated from the reduction in total heat flow to the liquid when the latter was covered by a floating shield of aluminum foil. The test data was compared with calculated results using the formula in [8]

$$Q_r=\frac{1}{\frac{1}{F}+\left(\frac{1}{\varepsilon_{cr}}+\frac{1}{\varepsilon_c}-2\right)}\sigma\pi R^2\left(T_{cr}^4-T_c^4\right), \tag{3}$$

where $F=(8/3)/\left(\frac{L}{D}+4\right)$ is the form factor.

Measurements in the range of L/D from 1.5 to 3.5 showed that radiative heat flow can be calculated with Eq. (3) with an accuracy sufficient for engineering purposes when the emissivity of the inside lateral surface $\varepsilon \ll 1$. Thus, with a cover temperature of 215°K, cover emissivity of 0.023, and neck height of 0.48 m, heat flow to the liquid decreases by 0.072 W when the shield is placed on the liquid; the calculated radiative heat flow for this case is 0.066 W.

Analysis of the test data shows that free convection has a substantial effect on heat transfer between the walls of the neck and the gas. It is expressed in an increase in heat transfer and a decrease in heat flow along the neck.

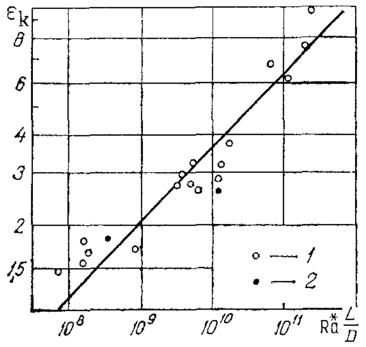

Fig. 2

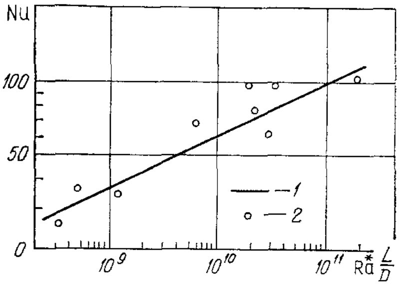

Fig. 3

Fig. 2. Dependence of ε_k on $Ra^*\frac{L}{D}$ for heat flow due to free convection: 1) nitrogen; 2) helium.

Fig. 3. Dependence of Nu on $Ra^*\frac{L}{D}$ for heat exchange between gas and wall: 1) using Eq. (1); 2) test data.

The test data obtained on the experimental cryostat and on commercial helium cryostats was analyzed using existing theoretical solutions [1-3, 8]. In the method in [2], the temperature dependence of the thermal conductivity of the neck material is approximated by a straight line. In reality, this dependence deviates quite a bit from linearity for metals, especially steel Kh18N10T, and can be satisfactorily approximated by the following quadratic trinomial:

$$\lambda_w = \lambda_0 + a\Delta T + b(\Delta T)^2.$$

Theoretical values of heat flow along helium-cooled necks, using the same approximation and assumptions similar to those made in [2], were found from the formula

$$\frac{mC_p h}{F_w + \frac{\varepsilon_k \lambda_g}{\lambda_w} F_g} = \Delta T\left(a + \frac{b}{2} - \frac{br}{C_p}\right) + \frac{\lambda_0 C_p^2 + aC_p r + br}{C_p^2}\left(\ln\frac{r + C_p\Delta T}{r}\right) + \lambda_0/2, \tag{4}$$

where a and b are constants. Calculations were performed using Eq. (4) with $\lambda_0 = 1.3$ W/m·K, $a = 0.11$ W/m·K^2, and $b = -2.6 \cdot 10^{-4}$ W/m·K^3 found from the temperature dependence of λ_w of steel Kh18N10T [9] in the range 50-150°K.

The best agreement was obtained between test and calculated data for the method in [8]. This method was based on the following assumptions: 1) the thermal conductivity of the neck material and the physical properties of the gas are independent of temperature; 2) the coefficient of heat transfer from the neck walls to the gas is constant along the height (α = const); 3) the thermal conductivity of the insulation (λ_{in}) on the outer surface of the neck is not a function of temperature.

The effect of temperature on the thermal conductivity of the neck material and gas was considered by determining their values at the integral mean temperature of the wall.

The methods in [1, 2] and Eq. (4) were obtained on the assumption that $\alpha = \infty$. It can be seen from Table 1 that the values calculated with these formulas agree with the experimental results to within 10-20%. The agreement improves as the approximation of the temperature dependence of thermal conductivity improves.

The methods in [3, 8] consider the imperfection of heat transfer. The first of these methods also considers the temperature dependence of the thermal conductivity of the wall material. The values calculated from these formulas with Nu equal to 4.36 (for forced laminar flow and type two boundary conditions) significantly exceed the experimental values, while there is satisfactory agreement at the Nu found from Eq. (1) (Table 1). Using experimental values of heat flow to liquid helium as a basis, it is possible to use the method in [8] to find the corresponding values of Nu. Heat flow through the gas in calculations by the

TABLE 1. Heat Flow (W) along Necks Cooled by Helium

Neck parameter		Calculation by the method							Expt.
L, m	T_{cr}, K	[1] $Nu=\infty$, $\lambda_w=const$	[2] $Nu=\infty$, $\lambda_w=\lambda_0+a(\Delta T)$	Eq. (6) $Nu=\infty$, $\lambda_w=\lambda_0+$ $+a(\Delta T)+$ $+b(\Delta T)^2$	[3] $\lambda_w=f(T)$ at Nu		[8] $\lambda_w=const$ at Nu		
					4,36	Eq. (1)	4,36	Eq. (1)	
Cryostat (Fig. 1)									
0,355	70	0,115	0,122	0,110	0,160	0,090	0,154	0,094	0,101
0,380	140	0,200	0,230	0,160	0,224	0,165	0,320	0,173	0,180
0,420	65	0,085	0,085	0,075	0,100	0,086	0,095	0,093	0,085
0,440	220	0,200	0,284	0,205	0,300	0,194	0,326	0,200	0,211
0,460	73	0,079	0,077	0,071	0,126	0,085	0,132	0,088	0,093
Cryostat KG-60/300									
0,480	57	0,080	0,080	0,079	0,104	0,095	0,100	0,092	0,086

methods in [1-3, 8] was taken into account by adding the quantity $\varepsilon_k\lambda_gF_g$ to the product λ_wF_w. Figure 2 shows the value of the convection coefficient ε_k that was used.

It can be seen from Fig. 3 that the values of Nu obtained agree satisfactorily with the values calculated from Eq. (3). The standard deviation is 30%. A 30% change in Nu within the investigated range changes heat flow to the liquid by only 6%.

Thus, this article established that heat flow to liquid helium along the neck of the surrounding vessel can be calculated with a mean error of 6% when Nu and ε_k are determined from Eqs. (1) and (2).

NOTATION

D, L, R, f, and F, diameter, height, radius, and area of surface and cross section of neck; C_p, specific heat of gaseous helium at constant pressure; m, rate of vaporization; r, heat of vaporization; q, heat flux; T, temperature; $\Delta T = T_{cr} - T_c$; ε, emissivity; ε_k, coefficient of free convection; λ, thermal conductivity (TC); σ, Stefan–Boltzmann constant; indices: cr, cover (warm boundary surface); w, wall; c, cold boundary surface; g, gas; Ra*, modified Rayleigh number calculated through the multiplier qL/λ_g; Nu, Nusselt number.

LITERATURE CITED

1. G. R. D. Hogg, "A note on conduction of heat down the necks of metal vacuum vessels containing liquid oxygen," Trans. Faraday Soc., 20, 327-330 (1924-1925).
2. A. Wexler, "Evaporation rate of liquid helium," J. Appl. Phys., 22, 1463-1467 (1951).
3. L. I. Roizen, Yu. V. Petrovskii, and G. R. Rubin, "Determination of heat flows along the neck of vessels with a cryogenic fluid," Inzh.-Fiz. Zh., 21, No. 5, 364-365 (1971).
4. B. V. Eliseev, Yu. P. Mordvinov, and L. P. Pasechnik, "Calculation of the cooling of a resistance thermometer bridge by helium vapors," Inzh.-Fiz. Zh., 31, No. 5, 894-904 (1976).
5. E. V. Onosovskii, Yu. A. Miroslavskaya, M. G. Kaganer, and N. V. Markelova, "Helium cryostats for laboratory investigations," Prib. Tekh. Eksp., No. 5, 205-206 (1982).
6. N. V. Markelova and M. G. Kaganer, "Study of heat transfer by free convection in a limited volume with heating from above," Inzh.-Fiz. Zh., 33, No. 4, 705-708 (1977).
7. N. R. Nagendra and M. A. Hirunaraynan, "Laminar free convection from vertical cylinders with uniform heat flux," Trans. ASME, Series C, 92, No. 1, 142-145 (1970).
8. M. G. Kaganer, Heat and Mass Transfer in Low-Temperature Thermally Insulated Structures [in Russian], Énergiya, Moscow (1979).
9. L. A. Novitskii and I. G. Kozhevnikov, Thermophysical Properties of Materials at Low Temperatures (Handbook) [in Russian], Mashinostroenie, Moscow (1975).