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NUMERICAL INVESTIGATION OF RADIATIVE HEAT EXCHANGE IN THE THROATS OF HELIUM CRYOSTATS

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A mathematical model of radiative heat exchange in the throats of wide-necked helium cryostats is analyzed. A comparison of the numerical results with known calculated and experimental data shows their good agreement.

The intensive development of cryogenic engineering and the ever-expanding scales of its adoption have required a more detailed analysis and improvement in the field. As a rule, the development of filling cryostats and refrigerator systems has been done on the basis of previous experience and simplified calculations. The problem of the further significant improvement of the construction and technology of their fabrication, especially at the level of the creation of cryogenic systems with a long continuous operating time, requires improvement of the methods of thermal calculations. An analysis of the existing methods of calculating heat inflow to a helium vessel through the throat shows that in setting up the heat balance of a wall element of the throat in combined heat exchange the decisive factors are heat conduction along the wall and heat exchange between the inner surface of the throat and the rising vapor of the cryogenic liquid. Composite heat exchange by radiation at the outer surface of the throat was taken into account in [1]. The majority of investigators neglect radiation in the closed inner cavity of the throat. Practice shows that this assumption is valid for systems with a long throat ($l \geqq 10$). But a considerable share of systems are made with cryostat throats 100 mm or more in diameter and with a relative length l = 3-5. Transverse shields are placed in such throats, as a rule, the distance between them being (1-3)D. In [2], it is emphasized that radiative heat exchange frequently makes a significant contribution to the total heat inflow. Using the results of [3], the author proposes to estimate the resultant radiant flux for the case when the emissivities of the warm and cold boundary surfaces differ from unity through the formula

$$Q_{\mathrm{r}} = \sigma\pi R^2 (T_{\mathrm{c}}^4 - T_{\mathrm{m}}^{4})/(1/F + 1/\varepsilon_{\mathrm{c}} + 1/\varepsilon_{\mathrm{m}} - 1). \quad (1)$$

Here F is an approximation of $\varepsilon_{\mathrm{re}}$ for the case of adiabatic pipes, the surfaces of which are gray and diffusely emit and reflect radiant energy while the end surfaces have an emissivity of unity. The results of calculations by Eq. (1) differ considerably from data obtained in accordance with [4]. Both means of determining the radiative heat inflow are based on assumptions rarely used in actual construction, and there is no experimental confirmation for helium temperatures. The fullest solution of the problem was obtained in [5]. Analog modeling of the process of radiative heat exchange in the throat permitted an estimate of the contribution of radiative heat inflow from the cover and throat. In the absence of transverse

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shields in the throat, radiative heat inflow is dominant over heat inflow along the wall. The authors indicate that blackening of the inner surface of the throat can reduce the radiative component, but no estimate of the effect of blackening is given. The calculations were made for $\varepsilon_m = 0.1$, $\varepsilon_c = 1$ and 0.1, and $\varepsilon_t = 1$ and 0.1, assigning a linear temperature profile in a throat unprotected by shields. The disagreement between the experimental and calculated data is 65%.

Two models of radiative heat exchange in the cylindrical cavity of the throat of a helium cryostat are investigated in the present paper. The cylinder of the throat or of the section between two transverse shields in it has a length L and a diameter D. Constant temperatures T_m and T_c and emissivities ε_m and ε_c are assigned at the surfaces of the mirror and the cover bounding the cylinder. The temperature field of the lateral surface is axisymmetric. The throat is filled with a diathermal medium; all the surfaces are gray and diffusely emitting and reflecting; the polarization of the radiant energy is suppressed in multiple reflections. The emissivity of the inner nonisothermal surface of the throat is taken from experimental data [6] as linearly dependent on temperature, $\varepsilon_t(y) = a + by$. The basis of the analysis is energy balance for arbitrary, infinitely small surface elements. In setting up the balance we start from the assumption that the radiant energy emitted by a surface ι is uniformly distributed over the hemisphere above this surface. The angular coefficient $F(\iota, j)$ determines that part of the radiant energy from the surface ι that reaches the surface j. Allowance for the contributions from all the elementary areas is accomplished by integration, leading to a system of three Fredholm integral equations of the second kind.

Model 1. It is well known that for cavities having a short length (l less than 4) the radiation flux varies considerably over the surfaces of the bottom and the cover [7]. In setting up the problem we allowed for the nonuniformity of the flux density distribution of the effective radiation of isolated surfaces. Designating the surface density of the effective flux of a cylindrical element of the throat at the point x_0 as $B_t(x_0)$, of an elementary ring of the cover at the point r_c as $B_c(r_c)$, and of an elementary ring of the bottom at the point r_m as $B_m(r_m)$ and setting up the heat balance, we obtain

$$B_t(x_0) = \varepsilon_t(y)\,\sigma\Delta T^4\,[y + T_t\,(x=0)/\Delta T]^4 + [1-\varepsilon_t(y)]\times$$
$$\times\Big[\int_0^l B_t(x)\,F_1(x_0,\ x)\,dx + \int_0^1 B_c(r_c)\,F_2(l-x_0,\ r_c)\,dr_c + \int_0^1 B_m(r_m)\,F_2(x_0,\ r_m)\,dr_m\Big], \tag{2}$$
$$B_c(r_c) = \varepsilon_c\sigma T_c^4 + (1-\varepsilon_c)\Big[\int_0^1 B_m(r_m)\,F_4(r_c,\ r_m)\,dr_m + \int_0^l B_t(x)\,F_3(r_c,\ l-x)\,dx\Big],$$
$$B_m(r_m) = \varepsilon_m\sigma T_m^4 + (1-\varepsilon_m)\Big[\int_0^1 B_c(r_c)\,F_4(r_m,\ r_c)\,dr_c + \int_0^l B_t(x)\,F_3(r_m, x)\,dx\Big],$$

where

$$F_1(\varphi,\ \psi) = 1 - |\varphi-\psi|\,\frac{2(\varphi-\psi)^2+3}{2[(\varphi-\psi)^2+1]^{1.5}};$$

$$F_2(\varphi,\ \psi) = 4\varphi\,\frac{1-\psi^2+4\varphi^2}{[(1+\psi^2+4\varphi^2)^2-4\psi^2]^{1.5}};$$

$$F_3(\varphi,\ \psi) = 8\psi\,\frac{1-\varphi^2+4\psi^2}{[(1+\varphi^2+4\psi^2)^2-4\varphi^2]^{1.5}};$$

$$F_4(\varphi,\ \psi) = 8\psi l^2\,\frac{\varphi^2+\psi^2+4l^2}{[(\varphi^2+\psi^2+4l^2)^2-4\varphi^2\psi^2]^{1.5}}$$

are angular coefficients obtained by differentiating the expression for the angular coefficient between two disks of equal radius located in parallel planes and having a common central normal. The derivation of the angular coefficients was verified by the closure rule, which follows directly from the law of conservation of energy. The kernels of Eqs. (2) have weak singularities as $x \to l$, $r_c \to 1$, $x \to 0$, and $r_m \to 1$. To isolate the latter we used the procedure when the integrand is written in the form of a sum of two functions, one of which contains the "entire" singularity but is integrated exactly, while the other, having no singularity, can be calculated with any given accuracy from one of the equations for approximate quadratures of [8]. This allows us to transform the system (2):

$$B_t(x_0) = \varepsilon_t(y)\,\sigma\Delta T^4\,[y + T_t(x=0)/\Delta T]^4 + [1 - \varepsilon_t(y)]\times$$
$$\times\left\{\int_0^l B_t(x)F_1(x_0, x)\,dx + \int_0^1 [B_c(r_c) - B_c(r_c = 1)]\,F_2(l - x_0, r_c)\,dr_c + \right. \tag{3}$$
$$\left. + B_c(r_c = 1)\,F_5(l - x_0) + \int_0^1 [B_m(r_m) - B_m(r_m = 1)]\;F_2(x_0, r_m)\,dr_m + B_m(r_m = 1)\,F_5(x_0)\right\},$$
$$B_c(r_c) = \varepsilon_c\sigma T_c^4 + (1 - \varepsilon_c)\left\{\int_0^l [B_t(x) - B_t(x = l)]\,F_3(r_c, l - x)\,dx + \int_0^1 B_m(r_m)F_4(r_c, r_m)\,dr_m + B_t(x = l)\,F_6(r_c)\right\},$$
$$B_m(r_m) = \varepsilon_m\sigma T_m^4 + (1 - \varepsilon_m)\left\{\int_0^l [B_t(x) - B_t(x = 0)]\,F_3(r_m, x)\,dx + \int_0^1 B_c(r_c)F_4(r_m, r_c)\,dr_c + B_t(x = 0)\,F_6(r_m)\right\},$$

where

$$F_5(\varphi) = 0.5\left[\frac{1 + 2\varphi^2}{\sqrt{1 + \varphi^2}} - 2\varphi\right];$$
$$F_6(\varphi) = 0.5\left[1 + \frac{\varphi^2 + 4l^2 - 1}{\sqrt{(1 + \varphi^2 + 4l^2)^2 - 4\varphi^2}}\right].$$

The density of the resultant radiation flux for an arbitrary surface element is

$$q_i^T = \frac{\varepsilon_i}{1 - \varepsilon_i}\,(B_i - \sigma T_i^4). \tag{4}$$

Simpson's quadrature formula was used to obtain the approximating algebraic system. The calculations were made by the method of simple numerical iteration. The iteration process was stopped when two succesive values of B_i coincided to within four decimal places. The calculation process was stable for all the adopted values of the parameters. The numbers of iterations ranged from 3-4 to 10-15, depending on the values of ε.

Adopting the assumption that the wall of the throat is isothermal, setting $\varepsilon_c = 1$ and $T_c = 0$, and performing elementary transformations, one can obtain a system of two equations analogous to those of [7, 9]. Control data were obtained for a particular case and compared with the results of [7]. The numerical results coincided for all significant figures.

Model 2. The mathematical model was constructed under the assumption of uniformity of the effective flux densities of the radiation of isothermal surfaces. This assumption permits considerable simplification of the system of equations (2), the kernels of the equations containing no singularities:

$$B_t(x_0) = \varepsilon_t(y)\,\sigma\Delta T^4\,(y + T_t(x = 0)/\Delta T)^4 + [1 - \varepsilon_t(y)]\times$$
$$\times\left\{B_m F_5(x) + B_c F_5(l - x) + \int_0^l B_t(x)\,F_1(x_0, x)\,dx\right\}, \tag{5}$$
$$B_c = \varepsilon_c\sigma T_c^4 + (1 - \varepsilon_c)\left[B_m F_7 + 4\int_0^l B_t(x)\,F_5(l - x)\,dx\right],$$
$$B_m = \varepsilon_m\sigma T_m^4 + (1 - \varepsilon_m)\left[B_c F_7 + 4\int_0^l B_t(x)\,F_5(x)\,dx\right],$$

where $F_7 = [l + \sqrt{1 + l^2}]^2$. In the limit as $l \to 0$, the problem comes down to the well-known simple case of heat exchange between two infinite plane surfaces:

$$B_c = \varepsilon_c\sigma T_c^4 + (1 - \varepsilon_c)B_m,\quad B_m = \varepsilon_m\sigma T_m^4 + (1 - \varepsilon_m)B_c. \tag{6}$$

With allowance for (4), from (6) after elementary transformations we obtain Eq. (1) not containing 1/F.

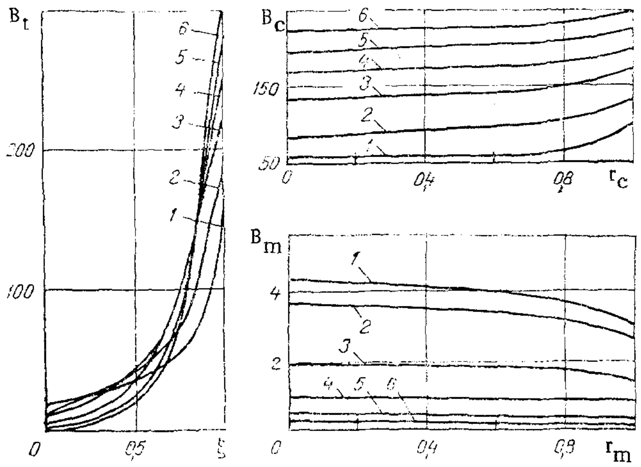

Fig. 1

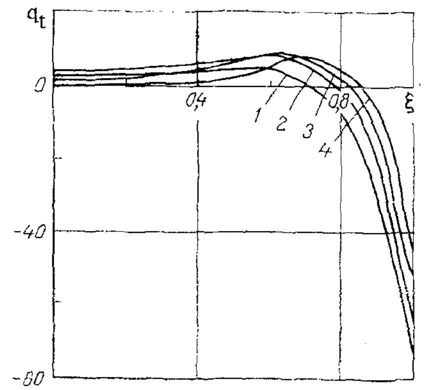

Fig. 2

Fig. 1. Distributions of effective flux density of radiation by the surfaces of the throat $B_t(x)$, the cover $B_c(r_c)$, and the mirror $B_m(r_m)$, W/m²: $\varepsilon_t(y) = 0.12 + 0.06y$; $\varepsilon_c = 0.05$; $\varepsilon_m = 0.9$; 1) $l = 1$; 2) 2; 3) 4; 4) 6; 5) 8; 6) 10.

Fig. 2. Distribution of flux density $q_t(x)$ of the resultant radiation of the throat, W/m²: $\varepsilon_t(y) = 0.12 + 0.06y$; $\varepsilon_c = 0.005$; $\varepsilon_m = 0.9$; 1) $l = 1$; 2) 2; 3) 4; 4) 8.

TABLE 1. Comparison of Values of Q_r Calculated in Accordance with the Present Work and [2, 5]

l	Cryogenic liquid	Heat inflow along the wall, W (expt.)	Heat inflow by radiation, W (calc. data)			Total heat inflow W (expt.)	Assignment of temp.
		[5]	[5]	[2]	the authors	[5]	
9,12	Nitrogen	$5{,}81\cdot10^{-2}$	$1{,}26\cdot10^{-2}$	$3{,}88\cdot10^{-2}$	$1{,}13\cdot10^{-2}$	$(6{,}3\pm1{,}35)\cdot10^{-2}$	Linear
7,39	Helium	$0{,}769\cdot10^{-3}$	$6{,}61\cdot10^{-3}$	$45{,}4\cdot10^{-3}$	$8{,}30\cdot10^{-3}$ $8{,}60\cdot10^{-3}$	$(11{,}4\pm2{,}1)\cdot10^{-3}$	I Parabolic
8,33	Helium	$0{,}567\cdot10^{-3}$	$5{,}67\cdot10^{-3}$	$41{,}7\cdot10^{-3}$	$6{,}33\cdot10^{-3}$ $6{,}36\cdot10^{-3}$	$(9{,}93\pm2{,}1)\cdot10^{-3}$	II Parabolic

Note. I and II are experimental curves according to [5].

The integral equations (5) were transformed by Simpson's rule to a system of linear algebraic equations, which were solved by the Gauss elimination method.

Many investigators have shown that the temperature curve is described by a complicated function containing exponential terms dependent on the total heat inflow. In designing a cryostat we solved the problem of combined heat exchange [10, 11], a component part of which is the determination of the characteristics of radiative heat exchange. For the first iteration the temperature profile can be assigned arbitrarily. The successive approximations are carried out until an assigned error in B_m is reached. With each iteration the temperature profile $T_t(x)$, the total heat inflow, and its components are refined.

Radiative heat exchange in the throats of helium cryostats is investigated in the present article as an important factor of combined heat exchange in cryogenic vessels. It was assumed that the wall temperature increases from the mirror shield toward the cover by a quadratic parabola law $y = x^2/l^2$. We chose a parabolic temperature profile, approximating the experimental data sufficiently closely (see Table 1), to study the qualitative character of radiative heat exchange in the throat. A similar assignment of the temperature was used in [9].

A numerical investigation of radiative heat exchange was made by the proposed models for a throat without shields in it and for sections of a throat with shields having temperatures of 78 and 42°K. The relative length l of the throat was set at from 0 to 10.

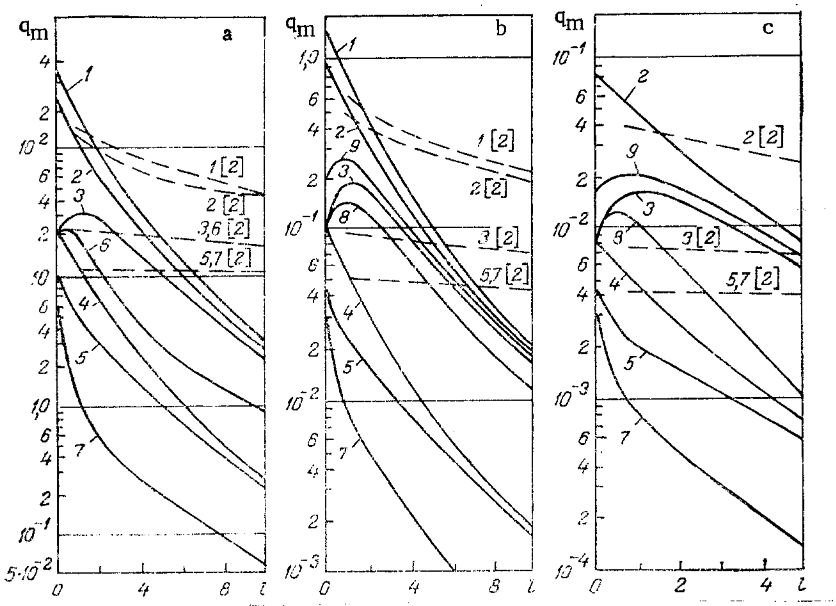

Fig. 3. Flux density q_m of the resultant radiation at the mirror in the throat of a helium cryostat as a function of the relative length of the throat for certain combinations of optical parameters, W/m^2: a) T_c = 300°K, T_m = 4.2°K; b) 78 and 4.2; c) 42 and 4.2. For $\varepsilon_t = 0.12 + 0.06y$: 1) ε_c = 0.9, ε_m = 0.9; 2) 0.5 and 0.9; 3) 0.05 and 0.9; 4) 0.5 and 0.05; 5) 0.05 and 0.05; 8) 0.05 and 0.5; 9) 0.1 and 0.9. For $\varepsilon_t(y) = 0.8 - 0.65y$: 6) ε_c = 0.05, ε_m = 0.9; 7) 0.05 and 0.05.

In Figs. 1 and 2 we present the results of calculations by the first model for the variant of a throat without transverse shields in it, i.e., T_c = 300°K and T_m = 4.2°K. The behavior of the $B_c(r_c)$ and $B_m(r_m)$ curves characterizes the nonuniformity of the flux density distribution of the effective radiation over the isothermal surfaces of the cover and mirror. At the same time, the resultant heat inflow to the surface of the liquid helium calculated from the first and second models differs insignificantly, by 1-2%. In Fig. 3 we present the dependence of the resultant flux density q_m on the relative length l for different ratios of emissivities. The data of Fig. 3a, b, and c allow one to estimate the efficiency of shields with a temperature of 78 and 42°K, respectively, as compared with the limiting case of an unprotected throat. The heat balance of the throat wall in radiative heat exchange at any height cross section is characterized by the $q_t(x)$ curves, which enable one to determine the zone of predominant radiation, located at a distance of $(1.0\text{-}0.7)x/l$ from the mirror, and the absorption zone, immediately adjacent to the mirror. Blackening the throat and mounting a mirror shield with ε_m = 0.05 at the lower edge of the throat considerably reduces the radiative heat inflow q_m. As was shown in [10], however, the total heat inflow is a nonadditive quantity in this case. Blackening the throat and mounting a shield at its lower edge, while leading to a decrease in q_m, increases the radiative load on the lower part of the throat, leading to an increase in the conductive component of the heat inflow. A considerable fraction of this heat is removed and carried off by vapors of the coolant, while the rest reaches the liquid. The presence of the throat wall with a temperature profile $T_t(x)$ and an emissivity $\varepsilon_t(T_t)$ exerts considerable influence on the behavior of the $q_m(l)$ curves and determines their properties in the region of relative lengths of from zero to one. The difference in these properties is determined by the ratio of the coefficients ε. If the contribution of the throat wall (6) is not taken into account, or is taken into account with approximations, through Eq. (1) in accordance with [2], the error in calculating the radiative heat inflow to helium increases with an increase in the length l. The results of calculations of a series of variants by the method of [2] are shown by dashed lines in Fig. 3.

The comparison of calculated and experimental data (see Table 1) was done from the data of [5], where they used a cryostat model enabling one to single out quite precisely the radiative component of the heat inflow incident on the surface of the coolant. Thanks to the presence of protective reservoirs containing coolant, the construction of the cryostat enables one to reduce the heat-balance equation for helium to two components, conductive and radiative. Measurement of the temperature of the inner surface of the throat wall makes it possible to calculate the conductive component with allowance for the radiative load on the wall and for heat exchange with the escaping vapors. Knowing the mass flow rate and estimating the heat inflow along the wall on the basis of the experimental data, we obtained data on the contribution of radiation from the cover and throat to the surface of the liquid helium and nitrogen. The calculations were made by the well-known method of [2] and, in accordance with the present method, from the experimental temperature profile taken from [5]. The method of [2] yields considerably overstated results. It must also be noted that the proposed method yields results in better agreement with the experimental data of [5] than the authors' calculations.

The proposed method enables one to obtain the radiative component of the heat balance, which appears in the system of equations of combined heat exchange for the determination of the total heat flux along the throat [10, 11], for any element of the throat. In addition, one can make a detailed analysis of radiative heat exchange in a closed cylindrical cavity of a nonisothermal pipe with a given temperature profile and isothermal cover and mirror surfaces; an investigation of the absolute and relative influence of the emissivity and the relative length l; an estimate of the relative contribution of each of the factors of heat inflow to any element of the system. In the case of a detailed analysis, one should use the first model, allowing for the nonuniformity of the density distribution of the effective radiation flux over the isothermal surfaces of the cover and mirror. Engineering calculations with a sufficient degree of accuracy can be made from the simplified second model, with the assumption of a uniform density distribution of the effective radiation flux over the isothermal surfaces of the cover and mirror.

NOTATION

L, D, R, length, diameter, and radius of the throat; $l = L/D$, relative length of the throat; Q_r, resultant radiative heat inflow; $F = 8/[3(L/R + 4)]$; T, temperature, ε, emissivity; X, coordinate with the zero point at the surface of the liquid helium; $x = X/D$, dimensionless coordinate; $\Delta T = T_t(x = l) - T_t(x = 0)$; $y = [T_t(x) - T_t(x = 0)]/\Delta T$, dimensionless temperature of the throat wall; σ, Stefan–Boltzmann constant; B, effective radiation flux density; ρ, coordinate with the zero point at the center of the disk; $r = \rho/R$, dimensionless coordinate; F_j, angular coefficient, where $j = 1, \ldots, 7$; q_m, resultant radiation flux density of the mirror; $\xi = x/l$; φ, ψ, formal parameters. Indices: t, throat; c, cover; m, mirror; re, reduced; r, radiative.

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EXPERIMENTAL STUDY OF THE THERMAL CONDUCTIVITY OF LITHIUM VAPOR

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The thermal conductivity of lithium vapor is measured. Equations are derived for calculation of the effective thermal conductivity and its components over a wide range of temperature and pressure.

In recent years lithium has become an important material in a number of technological fields. It is used in atomic energy devices and in space vehicle construction. This has stimulated interest in the thermophysical properties of lithium vapor.

In the case of alkali metal vapors, divergence has been found between experimental and calculated data (increasing from cesium to sodium) for both the atomic component of thermal conductivity and the effect of the dimerization reaction.

Until the present, experimental data on the thermal conductivity of lithium vapor has been absent from the literature, because experiments with lithium involve serious technological problems, due to the element's high boiling point and reactivity.

The thermal conductivity of lithium vapor was studied by the coaxial cylinder method, used previously for other alkali metals. However, because of the unique features of lithium and the higher temperature interval involved, the construction of the apparatus was changed. The measurement cell was connected to an evaporator. All of its components were formed of niobium alloys with high corrosion resistance to alkali metal vapors. Measurements were performed with two different gaps between the cylinders – 0.20 and 0.66 mm (Table 1).

Vapor was supplied to the intercylinder gap by two tubes from the evaporator.

The vapor pressure was determined from the saturated vapor elasticity curve [1] with thermocouples installed in the evaporator:

$$\lg P_s = 1.01325\cdot 10^5\left[8.5088-\frac{8363}{T}-1.02573\lg T-1.3091\cdot 10^{-4}T+1.08872\exp\left(-\frac{2940}{T}\right)\right]. \quad (1)$$

The measurement cell was placed within a thermostatic chamber. The internal volume of the thermostat was filled with high purity argon at a pressure of about $1\cdot 10^5$ Pa to prevent oxidation of the niobium components. The argon also served as a heat-transport medium, decreasing the contact thermal resistance of the thermocouples. A detailed diagram of the apparatus and description of the construction were presented previously in [2].

To monitor the operation of the device the thermal conductivities of inert gases were measured. Thermal conductivity values for argon and neon, measured before and after experiments with lithium, agreed well with each other. This indicated normal operation of the equipment.

Using data from the inert gas experiments, the contact thermal resistance ΔT_C was determined as a function of thermal flux liberated by the internal heater, and corrections were determined for the temperature head at the point of thermocouple attachment to the cylinder

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