filled, precautions were taken to prevent contact of the aldehydes with air. The error in the viscosity measurement was ±1%. We recorded 101 values of the dynamic viscosity (Table 1). We used the P—V—T data for the aldehydes from [4] in calculating the dynamic viscosity.

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PROBLEMS IN DESIGN AND CONSTRUCTION OF CURRENT INPUT LEADS MADE OF POROUS MATERIALS FOR CRYOGENIC ELECTRICAL EQUIPMENT

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Peculiarities in the design of porous current input leads are considered, such leads being cooled by axial filtration of a one-phase stream of a coolant, and a complex analysis of the heat transfer as well as the hydrodynamics involved here is presented in a more elementary form.

Current input leads are used for feeding an electric current from the "warm" region to cryogenic cables, windings of electrical machines, superconducting solenoids, electromagnets, energy storing devices, etc. [1-18].

In short cables (on the order of 1000 m long) the losses on cooling the current leads can, according to this author's estimates, exceed 50% of the total energy loss. The current lead often determines the reliability and the economics of the entire superconducting system [2].

One of the promising trends in development of economical and reliable gas-cooled current leads is the use of compact structures with a large heat-exchange surface, particularly porous conductors and electrical insulation [1, 11-17]. As porous current conductors, one can use ropes, braids, and meshes made of metallic electrically conducting materials, bundles of thin-walled capillaries, stacks of thin foil (perforated and corrugated, if possible), electrically conducting ceramics produced from metal powder by sintering, busbars made of microconductors in the form of a metallic "felt," metallic "foams," and combinations of any of these.

Practical experience in using porous current leads for superconducting devices testifies to their highly efficient performance [1, 11-17]. Current leads built with porous elements are very compact and ensure a high degree of utilization (80-100%) of the coolant enthalpy with very little thermal inertia. With porous current leads it is possible to vary their performance parameters over a wider range, owing to their wide range of thermophysical and electrophysical characteristics, also by varying the porosity and the permeability of the structural materials. Individual segments of current leads can be supplied with the necessary liquid coolant by forces of capillary suction. Difficulties in the practical application of porous current leads are related primarily to hydrodynamic losses, which become high when a coolant filtrates through a low-permeability material ($k < 10^{-10}$ m^2) [16], and to problems in producing agglomerate structures with ideal contact between particles.

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This author has attempted a complex analysis of the heat ransfer and the hydrodynamics with a current lead treated as a porous heat exchanger containing an array of nonuniform curvilinear channels which are cooled by filtration of the coolant and are characterized by such parameters as porosity ε, permeability k, etc.

The differential equations of heat and mass transfer in a porous current lead will be written as the system

$$\frac{d}{dx}\left[\lambda(T)\,S(1-\varepsilon)\,\frac{dT}{dx}\right]+\alpha_V S(T-T_L)+\frac{I^2\rho(T)}{S(1-\varepsilon)}=0, \tag{1}$$

$$G\,\frac{di}{dx}=\alpha_V S(T-T_L)+\frac{d}{dx}\left(\lambda_L S\varepsilon\,\frac{dT_L}{dx}\right), \tag{2}$$

$$\frac{dP}{dx}=-\frac{\eta}{k}\,w-\frac{\beta\gamma}{\sqrt{k}}\,w^2, \tag{3}$$

$$w=G/\gamma S, \tag{4}$$

where Eqs. (1) and (2) are the equations of energy, Eq. (3) is the equation of forces (equation of motion) [12], and Eq. (4) is the equation of continuity.

This system of equations (1)-(4) will be supplemented with a criterial relation characterizing the heat transfer in a porous body [3]:

$$\mathrm{Nu}=0{,}0175\mathrm{Pe};\quad \mathrm{Nu}=\frac{\alpha_V d^2}{6\lambda_L(1-\varepsilon)};\quad \mathrm{Pe}=\left(\frac{c_P\gamma}{\lambda}\right)_L w\,\frac{d}{\varepsilon}. \tag{5}$$

Available numerical data yield the relation $\mathrm{Nu} = 0.1\mathrm{Pe}^{1.25}$ [3]. In this author's view, this relation is inconsistent with known concepts about the nature of the dependence of the heat-transfer coefficient α_V on the thermal conductivity λ_L of the coolant

$$\alpha_V=0{,}1\,(c_P\gamma)_L^{1.25}\,wd^{-0.25}\,\lambda_L^{-0.25}.$$

The system of equations (1)-(4) will be further supplemented with expressions describing the temperature dependence of the thermophysical and electrophysical properties of the coolant [14, 16], on the following assumptions.

1. The electrical conductivity of a current lead depends linearly on the temperature

$$\rho(T)=\rho_0+\beta_1(T-T_0). \tag{6}$$

2. The thermal conductivity is represented by its mean-integral value [14]

$$\lambda_m=\frac{1}{T_1-T_0}\int_{T_0}^{T_1}\lambda(T)\,dT. \tag{7}$$

3. The pressure and temperature dependence of the coolant density obeys the Mendeleev–Clapeyron law

$$\gamma(T_L,P)=\frac{PM}{R_1T}. \tag{8}$$

4. Conductive heat transfer through the coolant and changes in the kinetic energy of the stream are negligible in comparison with other terms in Eqs. (2) and (3).

A Laplace transformation and a Heaviside expansion yield the solution to Eqs. (1)-(4), on the basis of relations (6)-(8), in the form of distributions of dimensionless analogs of the wall temperature θ, the coolant temperature θ_L, their difference ϑ, and the derivative of the wall temperature θ'_X (analog of the thermal flux Q(x) along the current lead):

$$\theta(X)=\sum_{i=1}^{3}c_{1i}\exp(p_iX)-\frac{4C}{B^2}, \tag{9}$$

$$\theta_L(X)=\sum_{i=1}^{3}c_{2i}\exp(p_iX)-\frac{4C}{B^2}, \tag{10}$$

$$\vartheta (X) = \sum_{i=1}^{3} c_{3i} \exp (p_i X), \tag{11}$$

$$\theta_X' (X) = \sum_{i=1}^{3} c_{4i} \exp (p_i X), \tag{12}$$

$$\theta = \frac{T - T_0}{T_1 - T_0}; \quad \theta_L = \frac{T_L - T_0}{T_1 - T_0}; \quad X = \frac{x}{l}; \quad B = 2I \sqrt{\frac{\beta_1}{\lambda_c}} \frac{l}{S(1-\varepsilon)}, \tag{13}$$

$$C = \frac{I^2 \rho_0 l^2}{\lambda_c (T_1 - T_0) S^2 (1-\varepsilon)^2},$$

while p_i ($i = 1, 2, 3$) are the roots of the characteristic equation

$$p^3 + Ep^2 + \left(\frac{B^2}{4} - D\right) p + \frac{EB^2}{4} = 0, \tag{14}$$

where

$$E = \frac{\alpha_V Sl}{c_p G}; \quad D = \frac{\alpha_V l^2}{\lambda_c (1-\varepsilon)}; \tag{15}$$

$$c_{1i} = \frac{p_i^2 \theta_0' + p_i (E\theta_0' - D\theta_{L0} - C) - EC}{p_i (p_i - p_j)(p_i - p_l)}; \tag{16}$$

$$c_{2i} = \frac{\theta_{L0} p_i^3 + p_i \left[\left(\frac{B^2}{4} - D\right) \theta_{L0} + E\theta_0'\right] - EC}{p_i (p_i - p_j)(p_i - p_l)}; \tag{17}$$

$$c_{3i} = \frac{-\theta_{L0} p_i^2 + p_i \theta_0' - \left(\frac{B^2}{4} \theta_{L0} + C\right)}{(p_i - p_j)(p_i - p_l)}; \tag{18}$$

$$c_{4i} = c_{1i} p_i, \tag{19}$$

with $i = 1, 2, 3$ and $j \neq l \neq i$.

Expressions (16)-(19) include the products of one of the roots p_1, p_2, and p_3 of the characteristic equation (14) by the difference between this root and each of the others.

In expressions (16)-(19) it is necessary to express the quantity θ_0' through the boundary condition for the "warm" end of the current lead $\theta(1) = \theta_1$:

$$\theta_0' = \frac{\theta_1 + \frac{4C}{B^2} + \sum_{i=1}^{3} \frac{\exp p_i [D\theta_{L0} + C(1 + E/p_i)]}{(p_i - p_j)(p_i - p_l)}}{\sum_{i=1}^{3} \frac{\exp p_i (p_i + E)}{(p_i - p_j)(p_i - p_l)}} \tag{20}$$

or, when $\theta_L(X = 1) = \theta_{L1}$ is given,

$$\theta_0' = \frac{\theta_{L1} + \frac{4C}{B^2} + EC \sum_{i=1}^{3} \frac{\exp p_i}{p_i (p_i - p_j)(p_i - p_l)}}{C \sum_{i=1}^{3} \frac{\exp p_i}{p_i (p_i - p_j)(p_i - p_l)}}. \tag{21}$$

Using the property of a current lead optimized according to the criterion of minimum heat influx to the cryogenic region $\theta_X'(1) = 0$, we obtain an additional expression relating the basic parameters of a porous current lead to the conditions of that optimum in the case $T \neq T_L$

$$\sum_{i=1}^{3} \frac{p_i^2 \theta_0' + p_i (E\theta_0' - D\theta_{L0} - C) - EC}{(p_i - p_j)(p_i - p_l)} \exp p_i = 0. \tag{22}$$

TABLE 1. Values of the Roots of the Characteristic Equation and of the Coefficients c_{ij}

Variant	p_1	p_2	p_3	$4C/B^2$	c_{11}
1	—104,722	3,352	8,340	0,04607	$-19{,}2\cdot10^{-4}$
2	—104,037	4,050	6,950	0,04607	$-19{,}9\cdot10^{-4}$

Variant	c_{12}	c_{13}	c_{31}	c_{32}	c_{33}
1	$4{,}63\cdot10^{-2}$	$-6{,}44\cdot10^{-5}$	$-16{,}56\cdot10^{-4}$	$16{,}11\cdot10^{-4}$	$-5{,}3\cdot10^{-6}$
2	$4{,}79\cdot10^{-2}$	$-16{,}23\cdot10^{-4}$	$-18{,}85\cdot10^{-4}$	$19{,}98\cdot10^{-4}$	$-1{,}13\cdot10^{-4}$

The practical design of a current lead was considered with, as an example, a simplified model of optimization of current leads for thermoanemometric probes [18]. Typical calculations were made on the basis of preceding relations for a porous current lead made of M1 copper in liquid helium. The characteristic dimension (diameter of wire, particle, pore, capillary) of the porous matrix was taken as d = 1 mm. The other data were: I = 3000 A, $\lambda_m = 479.3$ W/m·K, $\rho_0 = 6.4\cdot10^{-10}$ Ω·m, $\beta_1 = 0.48\cdot10^{-10}$ Ω·m/K, $T_1 = 300$°K, $T_0 = 4.2$°K, $[l/S(1-\varepsilon)]_{opt} = 5908$ m^{-1}, $G = 0.1883\cdot10^{-3}$ kg/sec, and $S = 300\cdot10^{-6}$ m^2. A current lead was first designed and optimized according to the criterion of minimum Q_0 for the case of ideal heat transfer from current lead to coolant ($T = T_L$) [12].

In the case of an ideal heat transfer

$$\theta(X)=\left(1+\frac{4C}{B^2}\right)\varphi(X)\exp\frac{A}{2}(X-1)-\frac{4C}{B^2}\left[1+\varphi(X-1)\exp\frac{A}{2}X\right], \tag{23}$$

where

$$\varphi(X)=\begin{cases}\dfrac{\sin ZX}{\sin Z}, & Z=\sqrt{B^2-A^2}/2,\quad B>A;\\[2mm] \dfrac{\operatorname{sh} ZX}{\operatorname{sh} Z}, & Z=\sqrt{A^2-B^2}/2;\quad A>B;\quad A=\dfrac{c_p Gl}{\lambda_m S(1-\varepsilon)};\\[2mm] X, & Z=0,\quad A=B.\end{cases} \tag{24}$$

For the given input data $A/2 = 6.115$, $4C/B^2 = 0.04607$, and $Z = 2.44$ are the numerical constants in Eq. (23).

Calculations based on the given relations for the case $T \neq T_L$ with the boundary conditions $\theta(1) = 1$ and $\vartheta_{Lo} = 0$ have yielded the roots p_i of the characteristic equation as well as the coefficients c_{ij} in the series expansions of the wall temperature and of the temperature drop from wall to liquid (gas) at any point along the current lead. Calculations were made for two variants: 1) constant flow rate of coolant G = const relative to ideal heat transfer and 2) maintenance of the relation $Q_0 = rG$ between the thermal flux and the coolant flow rate for a current lead partly immersed in liquid helium.

In the first variant the maximum temperature drop from wall to gas was ~8°K, corresponding to an ~2.7% lower utilization of the coolant enthalpy than during ideal heat transfer ($T = T_L$). In this case, moreover, the current lead was slightly "overloaded" with current and heat influx to the cryogenic region increased by 25%. While the relation between thermal flux and coolant flow rate was maintained (variant 2), nonideality of the heat transfer causes an ~6.5% simultaneous increase of the coolant flow rate and of the heat influx to the cryogenic region.

Numerical values of the roots of the characteristic equation as well as those of the coefficients c_{ij} are given in Table 1.

The dependence on the initial temperature difference from wall to coolant (ϑ_{Lo}, $T - T_{Lo}$), was estimated by calculating the heat flux Q_0 to the cryogenic region along the current lead at a constant coolant flow rate G = const. At Q_0 = 4.215, 4.155, 3.63, and 3.03 W, ($T - T_{Lo}$) was correspondingly 0, 0.06, 0.6, and 1.2°K.

TABLE 2. Values of the Performance Parameters of the Current Lead

I, A	Q_0, W	l/S, m^{-1}	G, kg/sec	G, liter/h	G_e, liter/h
0	0,78	2840	$0{,}37\cdot10^{-4}$	1,07	1,80
1000	1,49	2840	$0{,}71\cdot10^{-4}$	2,04	2,10
1600	2,10	2840	$1{,}00\cdot10^{-4}$	2,86	2,25
2000	2,92	2840	$1{,}39\cdot10^{-4}$	4,00	2,65

Accordingly, a temperature difference on the order of 1°K from wall to gas causes the heat influx to the cryogenic region Q_0 to drop 25% below its level during ideal heat transfer ($T = T_L$). The distribution of the wall temperature also changes in the cryogenic region, but insignificantly in the remaining part.

A numerical analysis of the performance parameters of porous current leads reveals that at coolant flow intensities from 0.5 to 1 kg/sec·m² the heat transfer from a current lead approaches ideal heat transfer from a porous body with the characteristic dimension (arithmetic mean dimension of pore, particle, channel) d = 1-2 mm or smaller (with a thermal flux density $q_V = 10^6$–10^7 W/m³). The temperature difference $T - T_L$ fluctuates then between a fraction of a degree and a few degrees. At high thermal flux densities q_V this fluctuation can reach tens of degrees.

The applicability of the model of ideal heat transfer to practical design of a porous current lead has been confirmed by, as an example, the development of a current lead for the KTG-20 cryoturbogenerator, built in the form of a model porous body consisting of a stack of capillary copper tubes (M1 copper, $d\times\delta = 1.6\times0.3$ mm) with radial drillholes. Theoretical and experimental values of the performance parameters of this current lead are given in Table 2.

Refinement of the mathematical model of a porous current lead taking into account the nonlinearity of the two relations $\lambda(T)$ and $\rho(T)$ requires a solution of Eqs. (1)-(4) by numerical methods. The problem of optimizing a current lead according to the criterion of minimum heat influx to the cryogenic region reduces to the Cauchy problem with a variable integration interval. The distributions of temperature and pressure along a porous current lead can be obtained from the expressions given here by applying the numerical Runge–Kutta procedure of the third order over the 4-80°K temperature interval, within which the nonlinearity of both relations $\lambda(T)$ and $\rho(T)$ is most pronounced. The maximum error of the linear model, relative to this nonlinear model, is within 20% in the distribution of the current lead temperature and in the distribution of the coolant pressure along the current lead as well as in the optimum value of the ratio $(l/S)_{opt}$. Therefore, it is hardly worthwhile to use this nonlinear model for the design of porous cryogenic current leads, a design which usually disregards the actual variance of $\lambda(T)$ and $\rho(T)$ characteristics depending on the purity of the material and the mode of its heat treatment. This applies also to materials of one type as, e.g., M1 and M2 copper. It is, therefore, more important to consider the actual values of $\lambda(T)$ and $\rho(T)$ when using the linear model than to resort to mathematical models on a higher level. A very important characteristic of a current lead is the mean temperature over its length θ_m (or T_m in natural units), easily calculated by way of integrating expressions (9) and (23) for real and idealized ($T = T_L$) heat transfer. Through the values of $\theta_m(X)$ one can determine the temperature distribution over the length of a current lead by measuring the potentials of the current lead, on the basis of the known $\rho(T)$ relation. Furthermore, the mean value $\theta_m(1)$ over the full length of a current lead has been found to be a very stable quantity for current leads which are made of certain grades of current-conducting materials and which operate under certain conditions. For current leads made of copper and partly immersed in liquid helium, e.g., $\theta_m = 0.30$–0.35 ($T_m = 90$–105°K) under conditions which are optimum according to the criterion of minimum heat influx to the cryogenic region (current $I = I_{opt}$). Under idling conditions ($I = 0$) $\theta_m = 0.2$–0.23 for the same current leads. Refinement of the $\lambda(T_m)$ value in conformance with these T_m values according to relations given in an earlier study [14], rather than by averaging θ_m in accordance with relation (7), can substantially improve the accuracy of calculations attainable with the linear mathematical model for a current lead. In the preceding example of a current lead made of M1 copper, we have $\lambda_m = 479.3$ W/m·K, while during idling $\theta_m = 0.215$ ($T_m \simeq 65$°K) and $\lambda(T_m) = 540$ W/m·K. Such a correction of λ increases the design value of the heat influx Q_0 to the cryogenic region and of the coolant flow rate G by ~30%.

The hydrodynamics of cooling a porous current lead by axial filtration of a one-phase coolant stream does in many ways determine the character of heat transfer from current lead to coolant, the regulation of the coolant flow rate, and the design of the cryostat for strength. In the case of a current lead with an independent coolant flow rate, in contrast to the case of one immersed in liquid, the flow of gas through the current lead is determined entirely by the boundary conditions with regard to pressure, by the current loading (thermal conditions) of the current lead, and by the hydrodynamic characteristics of the porous material (permeability and the coefficient β characterizing the pressure losses due to inertia). A very important item is calculation of the pressure in current leads so that the thermophysical characteristics of the coolant can be determined more precisely.

Expressions for calculating the pressure distribution along a current lead in natural units have been derived by this author from the system of equations (1)-(4), (8) with the boundary conditions $P(x = 0) = P_0$ or $P(x = l) = P_1$:

$$P(x) = \sqrt{P_0^2 - 2\frac{R_1}{Mk} j_L \int_0^x \eta(T_L) T_L(x)\,dx - 2\frac{R_1\beta}{M\sqrt{k}} j_L^2 \int_0^x T_L(x)\,dx}, \tag{25}$$

$$P(x) = \sqrt{P_1^2 + 2\frac{R_1}{Mk} j_L \int_x^l \eta(T_L) T_L(x)\,dx + 2\frac{R_1\beta}{M\sqrt{k}} j_L^2 \int_x^l T_L(x)\,dx}. \tag{26}$$

Expressions (25) and (26) can be simplified by omission of the inertia term, if the Reynolds number satisfies the condition

$$\mathrm{Re_m} = \frac{G\beta\sqrt{k}}{S\eta_m} = j_L \frac{\beta\sqrt{k}}{\eta_m} \ll 1. \tag{27}$$

As the mean value of the dynamic viscosity in expression (27) must be used the quantity

$$\eta_m = \frac{\int_0^x \eta(T_L) T_L(x)\,dx}{\int_0^x T_L(x)\,dx} = \frac{(\eta T_L)_m}{T_{Lm}}. \tag{28}$$

The hydrodynamic characteristics of porous current leads were calculated on the basis of these relations with the aid of a computer, over a wide range of the permeability k (10^{-8}-10^{-12}) and a wide range of the coefficient β (0.5-15). The distributions of the pressure, the Reynolds number, and the coolant velocity over the length of a current lead, also the variation of the mean Reynolds number and the mean velocity, are all shown in Figs. 1-3. The error curves of pressure calculation with and without the inertial component of the pressure drop in a porous current lead are shown in Fig. 4.

On the basis of these relations, one can make certain generalizations about the hydrodynamics of a porous current lead. The pressure distribution along a current lead is parabolic, determined by relations (25) and (26) (Fig. 1). As the permeability of a porous current lead decreases to 10^{-10}-10^{-11} m^2, axial filtration of a gaseous coolant through such a porous current lead of uniform cross section becomes impractical on account of the rising longitudinal pressure drop (up to several atmospheres). Most of the pressure drop (~90%) occurs along a segment of ~40% of the total lead length on the side of the warm end with a temperature of ~100-300°K (Fig. 1).

On this premise, it will be expedient then to increase the cross section of a current lead along that segment so as to reduce the loss of pressure. The efficacy of variable-section current leads was already suggested elsewhere [10], but on the basis of other criteria and quantitative relations. The form of the pressure distribution over the length of current lead confirms the validity of using the Clapeyron–Mendeleev equation as an approximation of the temperature and pressure dependence of the coolant density. A discrepancy of γ(T, P) values based on this equation for moderate pressures will appear only within the cryogenic region. In this region $\Delta P(x)$ is only a small part of the total pressure drop and, therefore, negligible.

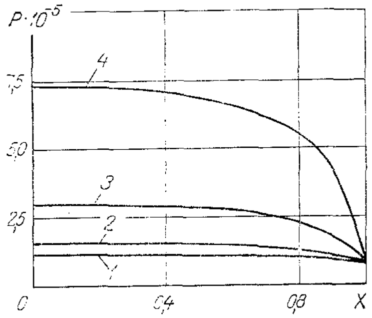

Fig. 1

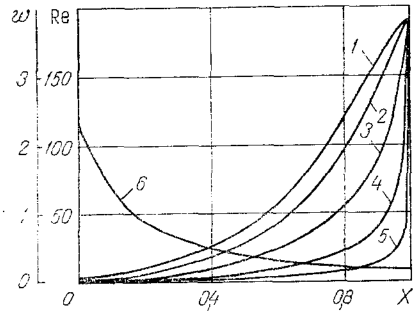

Fig. 2

Fig. 1. Pressure distribution over the length of an optimized current lead made of copper (M1) capillaries, at various values of the permeability k (m^2): 1) 10^{-8}; 2) 10^{-9}; 3) 10^{-10}; 4) 10^{-11}, with $\beta = 2.5$, $j_L = 0.634$ kg/m^2·sec, and $P \cdot 10^5$ in N/m^2.

Fig. 2. Distribution of the local coolant velocity w (m/sec) (curves 1-5) and the local Reynolds number (curve 6) over the length of a current lead, at various values of the permeability k (m^2): 1, 6) 10^{-8}; 2) 10^{-9}; 3) 10^{-10}; 4) 10^{-11}; 5) 10^{-12}, with $\beta = 2.5$.

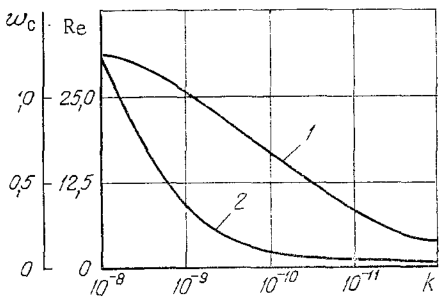

Fig. 3

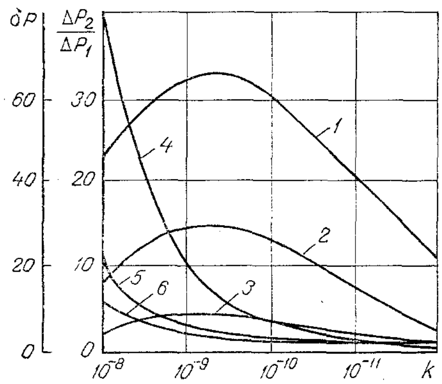

Fig. 4

Fig. 3. Dependence of the mean velocity (curve 2) and of the Reynolds number (curve 1) on the permeability of a porous current lead, with $j_L = 0.634$ kg/m^2·sec and $\beta = 2.5$.

Fig. 4. Dependence of the relative pressure calculation error δP and of the ratio of pressure drops $\Delta P_2/\Delta P_1$ on the permeability k of a porous current lead, with the inertial component included ($\beta \neq 0$) and with the inertial component disregarded ($\beta = 0$): 1, 4) $\beta = 15$; 2, 5) $\beta = 2.5$; 3, 6) $\beta = 0.5$, with $j_L = 0.634$ kg/m^2·sec.

The velocity of the filtrating coolant increases as the warm region of a current lead is approached, because the density of a coolant flowing at a constant mass rate decreases (Fig. 2). The density, in turn, changes because of two factors: the increasing temperature and the decreasing pressure of the coolant. As the dynamic viscosity η increases, the local Reynolds number decreases.

As the permeability of the material decreases, the mean filtration velocity decreases because of an increasing pressure drop across the length of the current lead. This statement is confirmed by the graphs depicting the dependence of the mean coolant velocity w_m on the permeability k of the porous material (Fig. 3). When k is changed from 10^{-8} to 10^{-12} with $\beta = 15$, e.g., then w_m decreases from 1.52 to 0.12 m/sec (Fig. 3). As to the mean Reynolds number, it decreases basically as a result of the decreased permeability of the material and of the characteristic hydrodynamic parameter $\beta\sqrt{k}$.

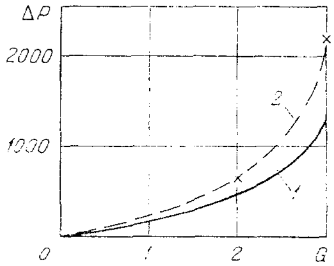

Fig. 5. Dependence of the pressure drop ΔP (N/m^2) across the length of a porous current lead on the coolant flow rate ($I = 0$, $k = 10^{-8}$, $\beta = 2.5$): 1) calculated curve; 2) measured curve.

For engineering calculations of the pressure in a cryostat, one can use the law of motion characterized by a pressure loss ΔP_2 proportional to the velocity squared ($\beta \neq 0$) and values of ΔP_1 obtainable from simplified relations ($\beta = 0$). The maximum error of pressure calculations on the basis of simplified relations does not, because of the smallness of the pressure drop ΔP, exceed 65% (remains on the average within 20-30%) relative to values based on the binomial law of filtration (Fig. 4). As to the pressure drop across the length of a current lead, however, here the error of calculations on the basis of the simplified relation is large. It is not practical to use the simplified relation for porous current leads with a permeability of 10^{-8}–10^{-11} m^2. Only at a permeability lower than 10^{-11} m^2, moreover, is the use of simplified relations for a given level q_V of thermal flux density permissible. The dependence of the pressure drop on the rate of coolant flow through a porous current lead is shown in Fig. 5, the graph indicating a satisfactory agreement between calculated and experimental data. When $T \simeq T_L$ in the case of porous current leads, then it is worthwhile to use the method of potentials for checking not only the temperature fields but also the hydrodynamic characteristics such as the pressure distribution over the length of a current lead.

The relations obtained here can be useful not only for the design of current leads but also for the performance analysis of porous current leads, cryogenic input leads, thermal bridges, and other components of cryogenic systems which feature a large longitudinal temperature gradient and are cooled by filtration of a one-phase coolant stream.

NOTATION

T (K), temperature; P (N/m^2), pressure; Q (W), thermal flux; I (A), electric current; λ (W/m·K), thermal conductivity; l (m) and S (m^2), respectively, length and the cross-sectional area of a current lead; ε (dimensionless), porosity of the material; k (m^2), permeability of the material; β (dimensionless), coefficient of the inertial term in the expression for hydraulic drag; c_p (J/kg·K), specific heat of the coolant; i (J/kg), enthalpy; G (kg/sec), coolant flow rate; ρ (Ω·m), electrical resistivity; β_1 (Ω·m/K), temperature coefficient of electrical resistivity; α_V (W/m^3·K), heat-transfer coefficient for a porous body; w (m/sec), coolant velocity; j_L (kg/m^2·sec), coolant flow intensity; γ (kg/m^3), coolant density; d (m), characteristic dimension of a porous body (diameter of particle, wire, pore, cell, capillary); M (kg/mole), molecular mass of the gas; R_1 = 8314.34 J/K·mole, universal gas constant; η (kg/m·sec), dynamic viscosity; Nu, Nusselt number; Re, Reynolds number; and Pe, Péclet number; subscripts: L, liquid (gas); m, mean value; 0, origin of coordinates (cryogenic region); 1, "warm" end of a current lead; and opt, optimum.

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