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ENERGY LOSSES IN COOLING OF CRYOGENIC CURRENT LEADS

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The effect of cooling system construction upon energy expended in cooling cryogenic current leads is studied for self-regulating and forced cooling by liquid helium.

When cryogenic equipment is utilized a cooling agent at temperature T_r is supplied continuously from a cryogenic device (refrigerator or liquifier) to the cryostat. Within the equipment being cooled it circulates at a higher temperature T_c, due to heat exchange with elements of the equipment, one end of which is at a low temperature T_0, while the other end is at a higher temperature T_ℓ. Usually the conditions of use require that the value of T_ℓ coincide with the temperature of the surrounding medium T_m. In a closed cycle system the cooling agent temperature decreases from a temperature T_c to T_r, which requires use of energy. The amount of energy thus used determines the cost of the equipment operation.

The goal of the present study is to analyze the cooling system with regard to energy expenditure in the cryogenic device for self-regulating and forced cooling of current leads. Some aspects of this problem for self-regulating cooling have already been considered in [1-4].

The value of the energy expenditure is determined by the product of the difference of the cooling agent exergies ΔE at temperatures T_c and T_r times the coolant mass flow rate G. The exergy difference is given by the expression

$$\Delta E(T_c,\ T_r) = [T_m S(T_c) - h(T_c)] - [T_m S(T_r) - h(T_r)].$$

With self-regulating cooling $T_r = T_0 = T_S$. Using known thermodynamic relationships for an ideal gas:

$$S(T_S) - S_L = \frac{r}{T_S}, \tag{1}$$

$$h(T_S) - h_L = r, \tag{2}$$

$$h = C_r T, \tag{3}$$

$$S(T_c) - S(T_0) = C_p \ln \frac{T_c}{T_0}, \tag{4}$$

one can calculate ΔE. Comparison with the data of [6] shows that the error in the calculation for helium does not exceed 5%.

We will study the behavior of the function $\omega = w/I(T_c)$ for self-regulated cooling of current leads, wherein a segment with temperature in the interval (T_0, T_c) is cooled by a flow rate G, while the remainder with temperature in the interval (T_c, T_ℓ) is cooled by a

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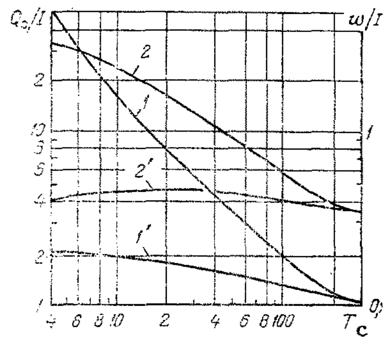

Fig. 1. Effect of T_c on value of Q_0/I and w/I for various current lead cooling methods: 1, 2) $G_p = G$; 1', 2') $G_p = 0.5G$; 1, 1') $Q_0/I\ (T_c)$; 2, 2') $w/I\ (T_c)$. Q_0/I, mW/A; w/I, W/A; T_c, K.

flow rate $G - G_p$, where $G_p = KG$. We will vary K over the interval (0, 1) and T_c over the interval (4.2-300) K. The helium flow rate is determined by solving the system of thermal balance differential equations for ideal heat exchange with the additional condition $G = Q_0/r$.

Results of calculations of specific energy losses for self-regulating cooling of the current loeads are shown in Fig. 1. They indicate that at $G_p = G$ minimal and practically constant energy losses are realized at T_c = (240-300) K. With decrease in the value of G_p the difference between the maximum and minimum values of ω decreases. The maximum is not clearly expressed, but corresponds to $T_c \approx 30$ K. At $G_p \leq G/2$ the maximum value of ω is less than 30% more than the minimum. Values of specific energy loss at T_c = 300 K and T_c = 4.2 K at $G_p = G$ coincide with the earlier results of [7].

It should be noted that the values of ω in Fig. 1 are calculated for a cooler efficiency of unity. The literature available to the authors offers no information on the dependence of cooler efficiency on temperature of the incoming coolant T_c, when $T_c < T_m$. An expression was presented in [8] for $\eta(T_r)$ at $T_c = T_m = 300$ K:

$$\eta(T_r) = 0.091T_r^{0.31}.$$

It follows from qualitative estimates based on the additiveness of energy that the efficiency of a cooling device operating between temperature levels T_c and T_r, where $T_0 < T_c < T_m$ can be defined with the expression

$$\eta^{-1}(T_r,\ T_c) = \eta^{-1}(T_r,\ T_m) - \eta^{-1}(T_c,\ T_m) + \eta^{-1}(T_m).$$

Then, using the data of Fig. 1, one can calculate the function $\omega(T_c,\ G_p)$ with consideration of cooling device efficiency.

The results presented above were obtained for satisfaction of the Wideman–Frantz relationship: $\rho\lambda = LT$. When one considers the real dependences $\lambda(T)$ and $\rho(T)$ of copper the energy losses decrease somewhat. For the type M1 copper widely used in the electrotechnical industry the reduction in energy loss comprises approximately 10%.

A superconductive state in the cold portion of the current lead, shunted by a superconductor, does not lead to a marked reduction in Q_0/I for self-regulating cooling, since at the critical superconductive temperature T_c = 16 K the specific thermal flux decreases by less than 10%.

Since near minimum thermal flux to the cooling zone and minimum energy expenditure can also be realized with removal of some portion of the helium flow from the cooling channels of the current lead, one should elevate the desirability of using the "cold," removed at an intermediate coolant temperature for cooling other elements of the cryostat (thermal bridges, radiation screens, supports), and then evaluate the total energy losses for the given coolant circulation pattern. The thermal intake to thermal bridges in the liquid helium range decreases rapidly with increase in flow rate. Thus, for an increase in flow rate by 10% as compared to the value for self-regulating cooling, the thermal intake to a thermal bridge of chromium–nickel–molybdenum stainless steel decreases by a factor of more than 10 times. The thermal intake from radiation screens also decreases markedly when they are cooled, since it is proportional to the fourth power of screen temperature.

The exergy difference depends significantly on the lower temperature involved. Therefore, we must verify whether a decrease in energy expenditure for current lead cooling can be achieved by cooling the lead only in its "hot" portion. It was found in [4] that for current leads the cold ends of which are maintained at (20-40) K, it is possible to obtain energy expenditures significantly less than required for total cooling, if only the portions with a temperature in the range (78-300) K are cooled by nitrogen vapor.

We will calculate the energy required to cool a current lead, the cold end of which is immersed in liquid helium, cooled by nitrogen vapor in the temperature range (78-300 K). We will assume that the helium is introduced into the cooler at the saturation temperature. The specific thermal flux from the current lead cooled by nitrogen vapor is 26.4 MW/A. With consideration of Eqs. (1)-(4) we find that the specific energy expenditure for nitrogen cooling is 0.1 W/A. If the current lead is immersed in liquid nitrogen to a sufficient depth the thermal intake to its adiabatic portion can be reduced almost to zero. Nitrogen evaporation then increases insignificantly. Energy losses to cooling of helium removed into the cooler due to evaporation from the thermal flux on the adiabatic current lead with temperature in the range (4.2-78) K comprise 0.8 W/A. The sum of energy expenditures for current lead cooling is then 0.9 W/A, which is 2.6 times greater than the minimum energy loss for a fully helium-cooled current lead. However with consideration of cooler efficiency, the value of ω_k becomes 1.8 W/A, which is approximately 30% less than for the completely helium-cooled lead.

For a similar cooling system, but with the nitrogen replaced by hydrogen, the energy expenditures for helium and hydrogen cooling are identical: ω = 0.42 W/A, ω_k = 1.3 W/A. Thus, it has been established that use of current leads with no cooling in the cold portions is energetically more efficient than use of completely helium-cooled leads. It must be kept in mind that with increase in temperature of the helium removed into the cooler above the calculated value energy losses will increase significantly. Moreover, with such a cooling configuration the necessary equipment may include two cooling devices. The question of using partially cooled current leads requires consideration from all sides.

Study of energy losses to cooling of thermal bridges shows that the same principles apply as in the case of energy losses for various methods of current lead cooling. Thus, for example, at a temperature T_c = (230-300) K and $G_p = G$ the energy expenditures remain practically constant at near minimum values. This can be explained by the fact that the thermal input to the thermal bridge due to radiation tends rapidly to zero in this tempeature interval. If we consider the thermal conductivity of the bridge material to be a linear function of temperature, and the radiant thermal input to be constant over the entire temperature range, it can be shown that the differential thermal balance equations for current leads and thermal bridges have an identical structure and solutions:

$$\frac{dQ}{dT}+\frac{I^2LT}{Q}-GC_r=0;\quad \frac{dQ}{dT}+\frac{Q_L k_1 FT}{Q}-GC_r=0.$$

We will now consider energy loss in forced cooling by gaseous helium. Then $T_0 > T_p > T_S$. The permissible coolant temperature rise in the superconductive winding fed by the current lead, $T_0 - T_p$, is determined by the condition of reliable maintenance of superconductivity and in the approximation of ideal heat exchange is equal to $(Q_0 + Q_a)/(GC_p)$. It is evident that for forced cooling the quantity $r_\ell = C_p(T_0 - T_p)$ is equivalent to the specific heat of vapor formation in self-regulated cooling. Since the helium exergy changes significantly near the the saturation temperature, the energy expenditure in forced cooling depends significantly on choice of the values T_p and r_ℓ.

Results of an energy loss calculation for forced cooling by helium are presented in Fig. 2 for $Q_a = 0$. It is interesting that with increase in the temperature T_0 the specific flow rate G/I increases markedly. Thus, at r_ℓ = 2600 J/kg the value of G/I increases 1.75 times for an increase in T_0 from 5 to 16 K. For r_ℓ = 7800 J/kg and increase in T_0 from 6 to 16 K the increase in G/I comprises 45%. This compensates the decrease in exergy differences and causes ω to vary only slightly, and somewhat exceed (up to 50%), depending on the value of r_ℓ,

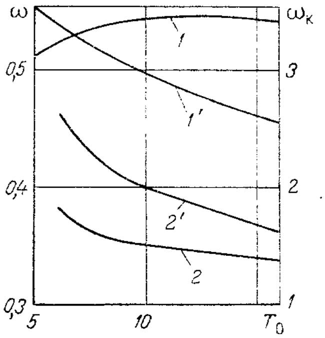

Fig. 2

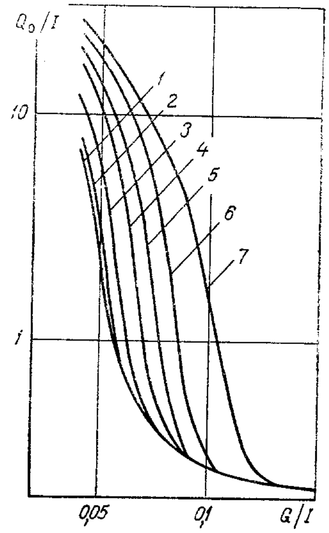

Fig. 3

Fig. 2. Specific energy loss vs temperature T_0 for various values of r_ℓ: 1, 1') r_ℓ = 2600 J/kg; 2, 2') r_ℓ = 7800 J/kg; 1, 2) $\omega(T_0)$; 1', 2') $\omega_k(T_0)$. ω and ω_k, W/A; T_0, K.

Fig. 3. Effect of T_c on function Q_0/I (G/I) at G_p = 0.5 G. Curves 1, 2, 3, 4, 5, 6, 7 correspond to T_c = 300, 240, 150, 90, 60, 30, and 10 K, respectively. Q_0/I, mW/A; G/I, g/sec·kA.

the value of ω for self-regulated cooling, equal to 0.344 W/A [7]. With consideration of cooling equipment efficiency, reduction in energy expenditure with forced cooling becomes even more possible. The value of ω_k calculated herein for self-regulated cooling, 2.64 W/A, coincides with that obtained previously in [8].

The effect of dividing the helium flow for specific thermal intake along the current lead was studied for forced cooling. Figure 3 shows the function Q_0/I (G/I) for G_p = 0.5 G at a number of T_c values with T_0 = 5 K, T_ℓ = 300 K. It follows from the figure that even at r_ℓ < 3400 J/kg removal of half the flow into the cooling device at a temperature $T_c \geq 60$ K does not increase the thermal intake into the cold zone, while specific energy expenditure decreases by 10-15%. However, the energy expenditure is still greater than for self-regulated cooling.

A further study was made of the effect of superconductivity on the value of ω_k for current leads of widely used electrotechnical materials. It proved to be the case that shunting by a superconductor made it possible to greatly reduce the value of ω_k. Thus, at r_ℓ = 2600 J/kg, T_0 = 8 K, T_c = 12 K, and leads of MZ copper, the value of ω_k decreases from 3.1 to 1.48 W/A, while M1 copper produces a reduction from 3 to 1.41 W/A, and electrotechnical aluminum, from 1.72 to 1.04 W/A. At T_0 = 5 K, T_c = 8 K, the corresponding reduction in energy expenditure for MZ and M1 copper and electrotechnical aluminum are as follows: from 3.5 to 1.82 W/A, from 3.4 to 1.79 W/A, and from 2.05 to 1.52 W/A, respectively. This occurs because of a significant reduction in thermal intake for shunting by a superconductor with forced cooling, which agrees with the results of [9].

NOTATION

Q, thermal flux; Q_0, thermal flux into cooled zone; Q_a, additional thermal flux into superconductive coil aside from that of current leads; Q_L, thermal flux per unit length of thermal bridge; T, temperature of current lead and coolant; T_S, boiling point of helium; S, specific entropy of coolant; h, specific enthalpy of coolant; Cp, specific heat of coolant; r, specific heat of coolant vapor formation; I, current; η, efficiency of cooling device; ω, specific energy expenditure at η = 1; ω_k, specific energy expenditure with consideration of function $\eta(T)$; ρ, resistivity; λ, thermal conductivity; k_1, coefficient in function $\lambda(T)$; L, Lorentz number; F, cross-sectional area of thermal bridge; r_ℓ, effective specified heat of vapor formation; h_L and S_L, specific enthalpy and entropy of coolant in liquid state.

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MECHANISM OF COAL COMBUSTION IN A FLUIDIZED LAYER OF COARSELY DISPERSED MATERIAL

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A system of one-dimensional steady-state balance equations is formulated for fuel, oxidizer, and energy. An approximate solution is obtained and compared to experiments on coal combustion in a fluidized layer.

In connection with the wide use of coal and other low-grade solid fuels, much promise has been shown by the process of combustion in fluidized bed furnaces, in which relatively coarse coal particles burn in a suspended state within a relatively low height fluidized layer of nonburning material. The system is inhomogeneous and consists of gas bubbles and a continuous phase (the solid particles suspended in the gas), which makes the character of coal combustion in a fluidized bed unique.

In recent years a number of two-phase models of coal combustion have been proposed [1, 2], based on information on gas bubble motion in a fluidized bed [3] and the heterogeneous reaction rate for combustion of residual coke [4].

The concepts of the two-phase model, which are valid for fluidized layers of fine particles of relatively low height, such as those used in heterogeneous catalytic reactors, are not completely applicable to shallow layers of relatively coarse particles used in low power furnaces. In the latter case the rate of bubble motion is less than the filtration velocity, and thus gas traversal through the layer with no contact with the solid material, so-called "bypass," is impossible. Moreover, in this layers including a zone near the grate, gas bubbles are generated, interphase exchange is quite intense, and traversal of gas streams through the layer without interaction with the dispersed particles is improbable.

Below we will propose a model for the process of combustion of a solid fuel in a fluidized bed of noncombustible material in the form of two interpenetrating continua: a gas

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