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STABILITY-OPTIMIZED, FORCE-COOLED, MULTIFILAMENTARY SUPERCONDUCTORS*

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ABSTRACT

A numerical program has been written to calculate the temperature-time history of a uniformly pulse-heated composite superconductor cooled by supercritical helium in forced convection. The program determines the maximum sudden temperature rise from which the conductor can still recover the superconducting state. The program includes the effects of (1) current sharing, (2) the temperature variation of the specific heat of both the matrix and the superconductor, and (3) the temperature variation of the heat transfer coefficient. Using this program, one may optimize force-cooled conductors with respect to stability by simultaneously varying the copper-to-superconductor (Cu/SC) ratio and the metal-to-helium ratio. Use of stability-optimized conductors allows a given stability level to be maintained for a particular field and bath temperature and the pressure drop and pumping losses to be reduced.

INTRODUCTION

In 1975, Hoenig and co-workers reported development of a novel cryostabilized superconductor consisting of a bundle of multifilamentary Cu/SC strands cooled by supercritical helium flowing in the interstices between the strands.[1] In one concept, the strands are fluted to increase the available area for heat transfer. In another concept, the heat transfer area is increased by twisting three substrands to make each strand.

Hoenig et al. have studied the recovery of the superconducting state in a long conductor following a sudden uniform temperature rise. Whether or not the conductor recovers depends on competition between transfer of heat from the metal to the helium and the production of joule heat in the metal. Nine different design parameters determine the details of this competition, namely: the total cross-sectional area of the conductor, A; the volume fraction of metal in the conductor, f_{co}; the volume fraction of copper in the metal, f; the cooled perimeter of the metal, P; the resistivity of the copper, ρ; the transport current in the conductor, I; the helium bath temperature, T_b; the magnetic field, B; and the heat transfer coefficient, h. Given these nine factors, it is possible to calculate the greatest heat per unit volume of metal, H, that can be deposited instantaneously in the conductor and still allow it to recover the superconducting state.

We should like to survey the behavior of H as a function of its nine arguments, but this task is too extensive to be undertaken easily. We can reduce the nine to seven by some simple considerations. First, P and h always occur in the product Ph. Second, for a given arrangement of strands of a given shape, the stability of a portion of the conductor is the same as that of the entire conductor. That means, for example, that if the original conductor is imagined to be composed of two smaller conductors in parallel, each of which has half the number of strands, half the cross-sectional area, and half the cooled perimeter of the original, then each half will have the same H as the original. Thus H can only depend on P/A and on I/A = J, the current density. Our original list of nine arguments can thus be reduced to the following seven: T_b, B, ρ, J, Ph/A, f, and f_{co}.

Seven arguments are still too many, and in this paper we deal with the more restricted problem of how H behaves as a function of the three variables Ph/A, f, and f_{co}, the remaining variables (T_b, B, ρ, and J) being fixed.

THE RESTRICTED PROBLEM

The analysis of the restricted problem is based on the observation that H has a maximum value H_{max} as a function of f and f_{co}, all other parameters being held fixed. To see this, consider what happens when f_{co} is held fixed and f is varied. If f is small, there is little copper, and when the superconductor is driven normal, the joule heat production is high. Such a conductor can only recover from a small excursion above the current sharing theshold temperature T_c. At the other extreme, if f is near 1, there is little superconductor, and the current density in the superconductor is close to the critical current density. Then the threshold temperature T_c is only slightly larger than the bath temperature T_b, and the heat the conductor can absorb and return below T_c is small. Some intermediate value of f is therefore best

If f_{co} is low, the total amount of metal is low, and at temperatures above T_c, the joule heat production is high. If f_{co} is near 1, the helium inventory is low, and the heat the conductor can absorb is again low. An intermediate value of f_{co} is best.

Let us imagine H plotted in three dimensions as a function of f and f_{co}. The argument given above says that if we hold either f or f_{co} constant and vary the other, H goes through a maximum. This means that if we cut the surface of H with any plane perpendicular to either the f or the f_{co} axis, the curve of intersection is concave downwards. We expect, therefore, that H has a single peak above the f-f_{co} plane, at which $H = H_{max}$.

If so, the contours of constant H in the f-f_{co} plane should be closed loops, and that is what is found by direct calculation. Shown in Fig. 1 are contours of H for the conductor shown in the inset. The values of T_b, B, ρ, J and Ph/A used are shown in the figure. For the geometry shown in Fig. 1, P/A = 1630 m^{-1}, so that $h = 1500\ W\ m^{-2}\ K^{-1}$. (Since h depends on both the metal and helium temperatures in a complicated way, the value quoted here is for the helium at T_b and the metal infinitesimally higher.) The value of h corresponds to a flow velocity of the helium in the interstices of 1 m s^{-1}. The contours are labeled with the values of H expressed in mJ cm^{-3} of metal.

The location of the maximum changes as the parameter Ph/A changes, for example, as the helium velocity changes. Figure 2 shows the coordinates of the maximum f, f_{co}, and H_{max} as functions of Ph/A for the given values of T_b, B, ρ, and J.

If a lower limit H_o is prescribed for H beforehand, then the smallest value of Ph/A we can attain is for the optimized conductor for which $H_{max} = H_o$. Consider the following argument: Suppose we have a conductor with a given f and f_{co} for which $H > H_o$. We can reduce Ph/A by reducing the helium flow velocity until $H = H_o$. Then, using the reduced value of Ph/A,

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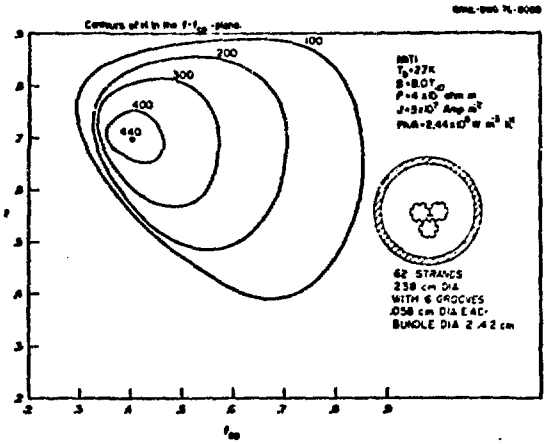

Fig. 1. Contours of H (mJ cm^{-3} of metal) in the f-f_{co} plane. The inset shows the details of the conductor geometry. The volume fraction of copper in the metal is f, and f_{co} is the volume fraction of the metal in the conductor.

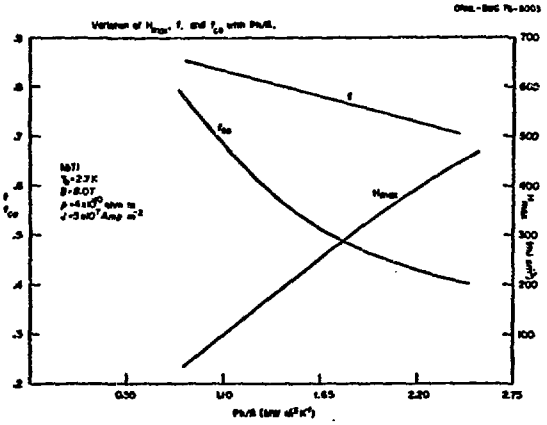

Fig. 2. Variation of H_{max}, f, and f_{co} with Ph/A.

we can optimize, i.e., increase H by appropriately choosing f and f_{co}. We continue this procedure until the optimized value of H, H_{max}, equals H_o. If the reduction in Ph/A has been substantial, this procedure may result in a substantial reduction in pressure drop and pumping power.

ILLUSTRATIVE EXAMPLE

For the geometry shown in Fig. 1, f_{co} = 0.63; let us consider a conductor for which f_{co} = 0.83 (Cu/SC = 5). With a helium velocity of 1 m s^{-1}, H = 200 mJ cm^{-3}, the pressure drop is 2.0 atm per 100 meters, and the pumping power is 0.27 kW km^{-1}. If we choose H_o = 200 mJ cm^{-3}, we find from Fig. 2 that $H_{max} = H_o$ when f = 0.80, f_{co} = 0.56, and Ph/A = 1.47 x 10^6 W m^{-3} K^{-1}. This value of Ph/A is about 60% of what it was for the original conductor. We can achieve the volume fraction of metal f_{co} = 0.56 by deepening the fluting grooves from 0.058 cm in diameter to 0.071 cm in diameter. This increases the cooled perimeter by about 5%, and allows h to be reduced from 1500 to 860 W m^{-2} K^{-1}, corresponding to a reduction in the helium velocity from 1 m s^{-1} to 0.52 m s^{-1}. The pressure drop is now 0.54 atm per 100 meters and the pumping power is 0.045 kW km^{-1}, equivalent to a reduction by a factor of 6.

The superconductor inventory is proportional to $(1 - f)f_{co}$. Using this formula, we find that the changes in f and f_{co} needed to reduce the pumping power increase the superconductor inventory by about about 7%. If we do not wish to pay the cost of the extra superconductor, we can carry out the optimization under the constraint of constant superconductor inventory, i.e., under the constraint of constant $(1 - f)f_{co}$ Doing this, we find that f = 0.81, f_{co} = 0.55; the flute diameter must be increased to 0.073 cm; the helium flow velocity is 0.54 m s^{-1}; the pressure drop is 0.56 atm per 100 meters; and the pumping power is 0.049 kW km^{-1}.

We see from this example that large reductions in pumping power can be achieved with no sacrifice in stability by using optimized conductors.

EFFECT OF BATH TEMPERATURE

The bath temperature used in the above illustration is low, and the lower the bath temperature the more stable the conductor. For fixed H_o, the lower the bath temperature, the lower the pumping power. However, since the pumping losses appear as heat at the helium bath temperature, they must be removed by the refrigeration system. One unit of heat removed at temperature T_b requires approximately 500 x $(4.2/T_b)$ units of work at room temperature. Although the pumping power decreases with decreasing T_b, the total room temperature work required could eventually increase with decreasing T_b. To test this possibility, the calculations described above were repeated for T_b = 1.9 K and 3.5 K. It should be noted that 1.9 K is very close to the lambda point for supercritical helium in the 3-5 atm pressure range. The pumping power at bath and room temperatures are shown in Table I.

TABLE I
Pumping Power vs Bath Temperature

T_b(K)	Pumping Power at Bath Temp (kW km^{-1})	Pumping Power at Room Temp (kW km^{-1})
1.9	0.025	28
2.7	0.045	35
3.5	0.18	110

Raising the bath temperature to 3.5 K increases the pumping power requirement at room temperature by a factor of 3, while reducing the refrigeration power required for all other heat inputs by only about 25%. Unless the pumping power is less than about 10% of the total refrigeration power, this is a bad bargain. If the bath temperature is lowered to 1.9 K, the pumping power required at room temperature is decreased by 18% and the rest of the refrigeration power is increased by 30%. Unless the pumping power is more than about 65% of the total refrigeration power, this is also a bad bargain.

NUMERICAL PROGRAM

The numerical program is based on a simple Runge-Kutta integration of the heat balance equations, assuming the temperature distributions in both the superconductor and the helium to be uniform. The physical parameters used in the program are as follows. Regarding (1) the details of current sharing, (2) the temperature dependences of the resistivity of copper and the specific heats of copper and NbTi, and (3) the critical data for NbTi, the assumptions made here are exactly those made in Ref. 2. For the sake of brevity, they will not be repeated here. Giarratano's modification of the Dittus-Boelter eqation is used for the heat transfer coefficient.[3] In the pressure range 3-5 x 10^5 N m^{-2} and the temperature range 2.5-4.5 K, Giarratano's equation can be approximated by

$$h = 1.06\,(T_{He})^{1.5}\,(T_{co})^{-0.716}\,v^{0.8}\,D^{-0.2} \qquad (1)$$

where h is the heat transfer coefficient in mW cm^{-2} K^{-1}, T_{He} is the helium temperature, T_{co} is the metal temperature, v is the helium flow velocity in the interstices in cm sec^{-1}, and D is the hydraulic diameter in cm. In the same temperature and pressure range the specific heat per unit volume of helium is within 20% of 2.75×10^{2} J m^{-3} K^{-1}, and this value is assumed throughout.

In order to understand the operation of the program, it is useful to consider the trajectories in the T_{He}-T_{co} plane. This plane is shown in Fig. 3. We are only interested in the octant below the line $T_{co} = T_{He}$ since the metal temperature T_{co} is always $\geq$ the helium temperature T_{He}. Also shown is the line $T_{co} = T_c$, the current quenching threshold temperature. Below this line on the T_{co} axis there is no joule heat production, as indicated in Fig. 3. The origin of Fig. 3 is at the point (T_b,T_b).

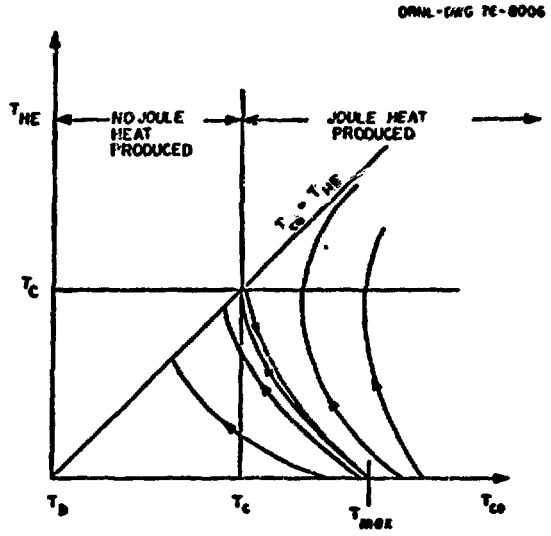

Fig. 3. Trajectories in the plane whose coordinates are the metal temperature (T_{co}) and the helium temperature (T_{He}).

We start by raising the metal to a temperature $T_{co} > T_c > T_b$ while the helium remains initially at the temperature T_b. These initial conditions are represented by a point (T_{co},T_b) on the T_{co}-axis. The temperature-time history is given by a curve in the T_{co}-T_{He} plane emerging from the point representing the initial conditions. Five typical curves are shown, marked with arrows pointing up and to the left. The sixth curve, with an arrow pointing down and to the right, will be discussed later.

The only equilibrium points of the system, i.e., the only points at which $dT_{co}/dt = dT_{He}/dt = 0$, are those points on the line $T_{co} = T_{He}$ in the square whose corners are (T_b,T_b), (T_b,T_c), and (T_c,T_c), and (T_c,T_b). The leftmost trajectory is shown ending on this line segment and represents recovery of the superconducting state. The rightmost trajectory shows the behavior in a case in which the conductor does not recover. We see that if the metal temperature falls below T_c the conductor recovers, while if the helium temperature rises above T_c, the conductor does not recover, and that these are the only two possibilities.

We should like to know the initial metal temperature T_{max} above which the conductor does not recover and below which it does. This temperature can be found by trial and error using the direct integration just described. However, such a procedure is time-consuming. It is possible to start the integration at a point near the point (T_c,T_c) and integrate backwards in time. A trajectory of this type is shown emerging from the point $(T_c + \Delta T,T_c)$ with an arrow pointing down and to the right. If ΔT is small enough, this trajectory will cross the T_{co} axis very close to the temperature T_{max}. Only a single integration of the differential equations representing the heat balance is necessary, and the computing time can be kept within tolerable limits.

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