CONF-760829--3

STABILITY-OPTIMIZED, FORCE-COOLED, MULTIFILAMENTARY SUPERCONDUCTORS*

Lawrence Dresner

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

For Presentation

Applied Superconductivity Conference
Stanford, California
August 17-20, 1976

—NOTICE—
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

By acceptance of this article, the publisher or recipient acknowledges the U.S. Government's right to retain a non-exclusive, royalty-free license in and to any copyright covering the article.

MASTER

* Research sponsored by the Energy Research and Development Administration under contract with Union Carbide Corporation.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
CONTRACT NO. W-7405-ENG-26

Lawrence Dresner[†]

If a lower limit H_0 is prescribed for H beforehand, then the smallest value of Ph/A we can attain is for the optimized conductor for which $H_{\max} = H_0$. Consider the following argument: Suppose we have a conductor with a given f and f_{co} for which $H > H_0$. We can reduce Ph/A by reducing the helium flow velocity until $H = H_0$. Then, using the reduced value of Ph/A ,

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_0 . 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 $f = 0.83$ ($\text{Cu}/\text{SC} = 5$). With a helium velocity of 1 m s^{-1} , $H = 200 \text{ mJ cm}^{-3}$, the pressure drop is $2.0 \text{ atm per } 100 \text{ meters}$, and the pumping power is 0.27 kW km^{-1} . If we choose $H_0 = 200 \text{ mJ cm}^{-3}$, we find from Fig. 2 that $H_{max} = H_0$ when $f = 0.80$, $f_{co} = 0.56$, and $Ph/A = 1.47 \times 10^6 \text{ W m}^{-3}$. 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 $860 \text{ W m}^{-2} \text{ K}^{-1}$, corresponding to a reduction in the helium velocity from 1 m s^{-1} to 0.52 m s^{-1} . The pressure drop is now $0.54 \text{ atm per } 100 \text{ meters}$ 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 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 $0.56 \text{ atm per } 100 \text{ meters}$; 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_0 , 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 $500 \times (4.2/T_b)$ 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 $T_b = 1.9 \text{ K}$ and 3.5 K . It should be noted that 1.9 K is very close to the lambda point for supercritical helium in the $3\text{--}5 \text{ atm}$ 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 equation is used for the heat transfer coefficient.³ In the pressure range $3\text{--}5 \times 10^5 \text{ N m}^{-2}$ and the temperature range $2.5\text{--}4.5 \text{ K}$, Giarratano's equation can be approximated by

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

where h is the heat transfer coefficient in $\text{mW cm}^{-2} \text{K}^{-1}$, 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 $2.75 \times 10^5 \text{ J m}^{-3} \text{K}^{-1}$, 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 carrying 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 right. 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.

REFERENCES

1. M. O. Hoenig, Y. Iwana, D. B. Montgomery, and A. Bejan, "Cryostabilized Single-Phase Helium Cooled Bundled Conductors For Large High Field Superconducting Magnets," Sixth Symposium on Engineering Problems of Fusion Research, San Diego, CA, Nov. 18-21, 1975, p. 586.
2. L. Dresner, J. R. Miller, G. W. Donaldson, "Propagation of Normal Zones in Composite Superconductors," Sixth Symposium on Engineering Problems of Fusion Research, San Diego, CA, Nov. 18-21, 1975, p. 266.
3. P. J. Giarratano, V. Arp, and R. V. Smith, *Cryogenics*, 11:385, 1971.