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Abstract

Subcooled flow of liquid nitrogen in microchannels is proposed as a means to enhance the stability of a superconducting magnet. Analysis shows high current density or a low stabilizer fraction is obtainable in a cryostable magnet. Increase in stability (using the Stekley criterion) is directly related to coolant velocity and coolant channel aspect ratio, however, there is a corresponding increase in pressure drop of the system. Another constraint is the coolant temperature rise, which is found to be a function of coolant residence time and the coolant to conductor ratio.

Introduction

Of the several methods for stabilizing a superconducting magnet, cryostabilization is often considered the most robust in that the superconductor can recover from an impulse perturbation, resulting in a local transition to the normal state, without quenching the magnet [1]. The weakness of cryostabilization is that when cooling is provided by pool boiling, the heat flux from the stabilizer into the cryogenic fluid has a

maximum that in practice limits the current density in the superconductor or requires a relative high ratio of stabilizer to superconductor. High-performance liquid-helium-cooled superconducting magnets often forego cryostabilization and rely on quenching, in which a high propagation velocity of the normal zone uniformly distributes the resistive state over the entire magnet before any local portion undergoes significant heating.

The discovery of high temperature superconductors (HTSs) made it possible to use liquid nitrogen, which is superior in many respects to liquid helium, as coolant for cryogenic stabilization. The stability of HTS magnets using conventional methods have been discussed by several researchers [2-13]. One critical issue which is yet to be resolved is protection of the magnet during a quench. The specific heat of the stabilizer (most likely silver) is rather high at liquid nitrogen temperature (77 K) and the propagation velocity of a normal zone is extremely low. Consequently, protection of a medium or large HTS magnet operating at liquid nitrogen temperature by self-propagation is not likely [8, 13] and it presents a challenging problem for magnet designers.

In this paper, we propose to provide full cryogenic stabilization of HTS magnets by using subcooled flow of liquid nitrogen through microchannels. Microchannel cooling is an emerging technology that has been used both in electronic packaging [14] and in microminiature refrigeration devices [15]. The maximum possible heat flux in this type of heat transfer is much larger than for pool boiling. We show that cryostability can be achieved by using microchannels while obtaining conductor performance equivalent to the best low-temperature superconductor designs. Relevant design parameters and limitations are identified. Finally, manifolding and fabrication related issues are discussed.

Analysis

The system to be analyzed is shown schematically in Fig. 1. A stabilizer (Ag) is bonded to a HTS and coolant channels are located on top of the stabilizer. A top plate (not shown in the figure) confines the flow. For reasons discussed later, we assume that the coolant flow direction is perpendicular to the current direction as shown in Fig. 1. In the microchannel system, the coolant channel is subdivided by conducting fins that are in good thermal contact with the stabilizer. We begin with the Stekly stability parameter α which is defined as

$$\alpha = G_c A / \theta H, \quad (1)$$

where G_c is the local critical heat generation rate per unit volume, $A = b(t_{Ag} + t_{HTS})$ is the cross-sectional area of the composite conductor (stabilizer plus HTS) in the direction of the coolant flow, t is thickness, b is the length of the system in the direction of the current, θ is the cooled perimeter, and H is the heat flux removed by the coolant. A system is cryostable if $\alpha < 1$. In Eq. (1), we have assumed that the current is completely transferred to the stabilizer and the heat generation rate G_c is [1]

$$G_c = \rho \lambda^2 J_c^2 / (1 - \lambda), \quad (2)$$

where ρ is the electrical resistivity of the stabilizer, $\lambda = t_{HTS} / (t_{HTS} + t_{Ag})$ is the fraction of the superconductor in the composite, and J_c is the critical current density of the superconductor. The walls of the coolant channels, with the exception of the top plate, are assumed to be made of metals or alloys with high

thermal conductivity. If the side wall thickness a is much smaller than the length of the conductor b , then the cooled perimeter is approximately (Fig. 1a)

$$\theta = b[1 + 2t_f/(w + a)], \quad (3)$$

where w is the width of a coolant channel, and t_f is the height of a coolant channel. The heat flux H at any axial location along the coolant flow direction is

$$H = h(T_w - T_o), \quad (4)$$

where h is the heat transfer coefficient, T_w is the temperature of the stabilizer, and T_o is the bulk coolant temperature. Substituting Eqs. (2), (3), and (4) into Eq. (1)

$$\alpha = \frac{\rho J_c^2 \lambda t_{HTS}}{(1 - \lambda)h(T_w - T_o)(1 + 2\eta)} \quad (5)$$

where η is the coolant channel aspect ratio

$$\eta = t_f/(w + a) \cong t_f/w. \quad (6)$$

In Eq. (6), we have assumed that $w \gg a$. It is seen from Eq. (5) that the stability of the system depends on, in addition to the usual parameters λ , ρ , h , etc.; the thickness of the superconductor t_{HTS} and the coolant channel aspect ratio η . For the purpose of comparison, a similar expression can be derived for a macrochannel system shown in Fig. 1b

$$\alpha^* = \frac{\rho J_c^2 \lambda^* t_{\text{HTS}}^*}{(1 - \lambda^*) h^* (T_w - T_0)^*} \quad (7)$$

where the superscript * denotes the macrochannel system. Assuming that $t_{\text{HTS}} = t_{\text{HTS}}^*$ and $(T_w - T_0) = (T_w - T_0)^*$, dividing Eq. (5) by Eq. (7) gives

$$\frac{\alpha}{\alpha^*} = \frac{h^* t_{\text{Ag}}^*}{h t_{\text{Ag}}} \left(\frac{1}{1 + 2\eta} \right). \quad (8)$$

If we further assume that $t_{\text{Ag}}^* = t_f + t_{\text{Ag}}$, then Eq. (8) becomes

$$\frac{\alpha}{\alpha^*} = \frac{h^* (1 + \zeta)}{h (1 + 2\eta)} \quad (9)$$

where ζ is the coolant to stabilizer ratio

$$\zeta = t_f / t_{\text{Ag}} \quad (10)$$

Equation (8) or (9) determines the improvement in cryostability when switching from a macrochannel to a microchannel system. One would like to have an α ratio as small as possible in order to maximize the gain in stability. However, there are other design constraints which also depend on the parameters that appear in Eq. (9) and we are going to address these issues next.

The pressure drop increases as the size of the system decreases. Recently reported experimental results [6] indicate that there is some difference in pressure drop between a microtube and a larger system which satisfies the conventional correlations. However, the difference is not very large and for the

purpose of comparison here we shall ignore this difference and employ the conventional formula for both the micro and the macro systems. We consider the flow to be laminar (the analysis for turbulent flow can be carried out in a similar manner) and the pressure drop for the microsystem is

$$\delta P = f (\ell/d)(\gamma v^2/2) = (64/Re)(\ell/d)(\gamma v^2/2) = 32 \mu \ell v/d^2, \quad (11)$$

where $f = 64/Re$ is the friction coefficient, ℓ is the axial length in the flow direction, Re is the Reynolds number, d is the hydraulic diameter, γ is coolant density, μ is coolant viscosity, and v is coolant average velocity. The hydraulic diameter of the microchannel is

$$d = 2 w t_f / (w + t_f). \quad (12)$$

The pressure drop and the hydraulic diameter for the macrochannel are

$$\delta P^* = 32 \mu \ell^* v^* / (d^*)^2, \quad (13)$$

$$d^* = 2 b t_f^* / (b + t_f^*). \quad (14)$$

Since b is usually much larger than t_f^* and $\ell = \ell^*$, Eqs. (11) to (14) can be combined and simplified to give

$$\frac{\delta P}{\delta P^*} = \frac{v}{v^*} \left[\frac{t_f^*}{t_f} (1 + \eta) \right]^2. \quad (15)$$

The heat transfer coefficient of laminar flow in microchannels can be evaluated by the following correlation [6]

$$h = 0.000972 k (\gamma/\mu)^{1.17} (\text{Pr})^{0.333} d^{0.17} v^{1.17}, \quad (16)$$

where k is the thermal conductivity of the coolant, and Pr is the Prandtl number of the coolant. Equation (16) is also applicable to macrochannels and we can obtain the following equation for h/h^*

$$\frac{h}{h^*} = \left(\frac{t_f}{t_f^*} \right)^{0.17} \left(\frac{1}{1+\eta} \right)^{0.17} \left(\frac{v}{v^*} \right)^{1.17}. \quad (17)$$

Substituting Eq. (17) into Eq. (9)

$$\frac{\alpha}{\alpha^*} = \left(\frac{t_f^*}{t_f} \right)^{0.17} \left(\frac{v^*}{v} \right)^{1.17} (1+\zeta) \frac{(1+\eta)^{0.17}}{(1+2\eta)}. \quad (18)$$

A second constraint is the overall coolant temperature rise through the microchannels. To prevent boiling in the coolant channels, the coolant temperature rise must be kept within a certain limit. The coolant temperature rise δT can be calculated by applying an energy balance for the system

$$\delta T = (G_c/\gamma C_p) \tau (1 + a/w)/\xi, \quad (19)$$

where C_p is the specific heat of the coolant, τ is the coolant residence time

$$\tau = \ell/v, \quad (20)$$

and ξ is the coolant to conductor ratio

$$\xi = t_f / (t_{Ag} + t_{HTS}). \quad (21)$$

A third constraint is related to the cooling efficiency of the side walls of the microchannels. These side walls are fins which serve to increase the heat transfer area between the conductor and the coolant. Using an one-dimensional approximation [7], the temperature at the tip of a fin (T_{tip}) can be calculated by

$$T^* = \frac{1}{\cosh\left[(2h / k_w a)^{1/2} t_f\right]} \quad (22)$$

where k_w is the thermal conductivity of the side walls of the coolant channel and T^* is the dimensionless tip temperature

$$T^* = (T_{tip} - T_o) / (T_w - T_o). \quad (23)$$

In order for the entire side wall to be effective, T_{tip} should not deviate too much from T_w .

Results

Results of the previous analysis are presented in two parts. First, we present a comparison between a microchannel and a macrochannel system. Then an example is worked out to demonstrate how various design constraints affect a specific microchannel system.

Figure 2 shows the variations of the ratio α/α^* with η and ζ , calculated by Eq. (18) with $v/v^* = 1$ and $t_f/t_f^* = 0.2$. It is clear that stability can be enhanced by using

a microchannel system as compared to a macrochannel system. It is seen that the ratio α/α^* decreases sharply with η until η reaches approximately 10, then the variation becomes more gradual. Figure 3 shows the variations of the pressure ratio $\delta P/\delta P^*$ with η and the ratio t_f/t_f^* , calculated by Eq. (15) with $v/v^* = 1$. The pressure ratio increases sharply with η and decreases with the ratio t_f/t_f^* (note that the vertical scale in Fig. 3 is logarithmic). Thus, cryostability can be enhanced by using microchannels, but the price one has to pay is increased pressure drop when compared to macrochannel system. The larger the gain in stability, the higher the pressure drop. Larger pressure drop could have significant impact on structural integrity, pumping power, and other system considerations.

As an example, we shall carry out the following calculations to determine the stability margin of a liquid nitrogen-cooled microchannel system and to demonstrate how the various design constraints affect a given system. We assume that the stabilizer is made of silver. Assuming that the following parameters are provided as input:

$$J_c = 10^9 \text{ A/m}^2, T_w - T_0 = 20\text{K}, t_{\text{HTS}} = 150 \text{ } \mu\text{m}, t_{\text{Ag}} = 150 \text{ } \mu\text{m}, \\ t_f = 200 \text{ } \mu\text{m}, w = 40 \text{ } \mu\text{m}, a = 10 \text{ } \mu\text{m}, \text{ and } v = 5 \text{ m/s}.$$

The electrical resistance of pure annealed silver at $T = 80\text{K}$ is $\rho = 2.90 \times 10^{-9} \text{ } \Omega\text{m}$. From these values, we obtain the following

$$\eta = t_f/w = 5, \\ \lambda = t_{\text{HTS}}/(t_{\text{HTS}} + t_{\text{Ag}}) = 0.50 \\ d = 66.7 \text{ } \mu\text{m},$$

$$\begin{aligned} \text{Re} &= 1703, \text{ and} \\ h &= 1.624 \times 10^4 \text{ W/m}^2\text{-K.} \end{aligned}$$

The flow is laminar because the Reynolds number is less than 2300. Substituting these values into Eq. (5)

$$\alpha = 0.122 < 1.$$

Thus the system is not only stable but also has a large margin which can be used to reduce pressure drop, increase the fraction of the superconductor in the composite, etc. The pressure drop can be calculated by Eq. (11) and the results are

$$\begin{aligned} \delta P &= 0.284 \text{ MPa; if } \ell = 0.05 \text{ m, and} \\ \delta P &= 0.568 \text{ MPa; if } \ell = 0.10 \text{ m.} \end{aligned}$$

The pressure drop increases linearly with the flow length ℓ . At $\ell = 0.10$ m, the pressure drop is already close to 5.7 atms. In order to keep the pressure drop at acceptable levels, the flow length should be minimized. This is why we choose to make the coolant flow in a direction perpendicular to the direction of the current shown in Fig. 1. Only in this configuration one has the flexibility of varying the flow length. This has major impact on the design of superconducting magnets and the manifolding systems.

From the values given previously in the example, we can calculate the heat generation rate per unit volume of the composite conductor and some other relevant parameters

$$G_c = 1.45 \times 10^9 \text{ W/m}^3,$$

$$\xi = 0.666, \text{ and}$$

$$a/w = 0.25$$

The density and specific heat of liquid nitrogen at $T = 80\text{K}$ are $\gamma = 807.3 \text{ kg/m}^3$, and $C_p = 2.051 \text{ kJ/kg-K}$; respectively. If we choose a flow length of $\ell = 0.05 \text{ m}$, then $\tau = 0.01 \text{ s}$. Substituting these values into Eq. (19) resulted in $\delta T = 16.5\text{K}$. This temperature rise is not unreasonable for liquid nitrogen or nitrogen/neon mixture.

Finally we must check the tip temperature which should not deviate substantially from the stabilizer temperature. Figure 4 shows the variation of the parameter $k_w a/h$ with the coolant channel height and the dimensionless tip temperature, calculated by Eq. (22). The thermal conductivity of silver (k_w) at $T = 80\text{K}$ is 471 W/m-K . From the values given in the example, we have

$$t_f = 200 \text{ mm}, \text{ and } k_w a/h = 2.90 \times 10^{-7}.$$

From either Fig. 4 or Eq. (22), we obtain

$$T^* = (T_{\text{tip}} - T_o)/(T_w - T_o) = 0.877, \text{ and}$$

$$T_{\text{tip}} - T_o = 17.54\text{K}$$

Therefore, instead of 20K , the temperature difference available for heat removal at the tip is 17.54K .

It should be noted that the example presented here is to demonstrate that cryogenic stabilization of high temperature superconducting magnets operating at liquid nitrogen temperature is technically feasible by using microchannels. The results presented are not optimized. In an actual system, a designer should attempt to maximize the performance of the conductor without violating any of the constraints specified for a given application.

Discussion

Compared to a conventional superconducting magnet, magnets using microchannel cooling will require significantly more manifolds. The design example showed that it is theoretically possible to obtain high current density in a cryostable magnet, but with accompanying high pressure drop. In order to keep system pressure drops practical, it will be necessary to establish short flow paths, and we have suggested running flow perpendicular to the current in Fig. 1. For a pancake magnet formed by tape conductors there is a good match to width of conductor and length of coolant flow. An alternate configuration would be to run the coolant flow in the direction of the current but have periodic flow inlets and outlets. Such an arrangement could make winding of a large magnet complicated.

The fabrication of microchannels in conductor stabilizer will probably require more precision than is typical in the fabrication of superconductors. The channels could be etched onto the stabilizer after final conductor processing or could be manufactured on a separate piece and postbonded to the stabilizer. Clearly, the fabrication costs of the microchannels must not be excessive for the stabilization technique to be viable.

Although considerable progress continues to be made, HTS wire capable of producing high current density at 77 K in high-field magnets does not yet

exist. However, HTS wire operating at somewhat lower temperatures may be available in the near future. The microchannel approach described here is readily adapted to lower temperature operation. Pure liquid nitrogen can be subcooled considerably below the boiling point with the minimum temperature depending on pressure. A mixture of nitrogen and a small amount of neon can lower the freezing point of the cryogen even further.

Conclusions

The use of subcooled liquid nitrogen flowing in microchannels can successfully achieve cryostabilization of HTS magnets. The current densities achievable are comparable to the best values in contemporary superconductor magnets. The high stability is attained at the cost of a significant but not inordinate pressure drop in the cooling channels. This pressure drop can be readily accommodated without by flowing the coolant transverse to the current flow.

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FIGURE CAPTIONS

Fig. 1. Schematic of stabilization systems.

Fig. 2. Stability parameter ratio versus coolant channel aspect ratio for different coolant to stabilizer ratios.

Fig. 3. Pressure drop ratio versus coolant channel aspect ratio for different coolant channel height ratios.

Fig. 4. Fin cooling area parameter versus cooling channel height for different dimensionless tip temperatures

(a) microchannel system

(b) macrochannel system

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