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Temperature profile evolution in quenching high-T_c superconducting composite tape

ZIAUDDIN KHAN[1,*], SUBRATA PRADHAN[1] and IRFAN AHMAD[2]
[1]Institute for Plasma Research, Near Indira Bridge, Bhat, Gandhinagar 382 428, India
[2]Shibli National College, Sikandarpur Market Road, Paharpur, Azamgarh 276 121, India
[*]Corresponding author. E-mail: ziauddin_khan@rediffmail.com

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Abstract. Irreversible normal zones leading to quench is an important aspect of high-temperature superconductors (HTS) in all practical applications. As a consequence of quench, transport current gets diverted to the matrix stabilizer material of the high-T_c composite and causes Joule heating till the original conditions are restored. The nature of growth of the resistive zone in the superconductor greatly influences the temperature evolution of the quenched zone. In this investigation, a complete mathematical analysis of the temperature profile evolution following a quench in a HTS has been carried out. Such prediction in temperature profile would aid the design of HTS tape-based practical applications in limiting the thermal stress-induced damages in off-normal scenarios.

Keywords. Quench; high-T_c; yttrium barium copper oxide tape; local disturbances.

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1. Introduction

High-temperature superconductors (HTS) are attractive candidates for several practical applications such as fault current limiters, high-voltage DC transmission lines, superconducting magnet storage devices etc. [1–9]. Also, the HTS have the advantage of operating at 80 K, i.e., liquid nitrogen (LN_2) environment, which reduces the operating cost associated with the cryogen. Further, handling of LN_2 is very easy compared to other cryogens. However, HTSs have inevitable off-normal operating scenarios. In such off-normal scenarios, the superconductivity is temporarily lost and the superconductor is said to have 'quenched'. The quench of the superconductor generally happens when one of its intrinsic parameters such as transport current, total perpendicular magnetic field, operating temperature or operating maximum strain level exceeds a critical limit. In practice, such consequences may arise, for example, if the transport current is accidentally increased beyond the critical value or the background field exceeds the critical value or the coolant temperature exceeds the critical value as a result of temporary loss of flow or the

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electromagnetic strain resulting from the interaction of the transport current and the field exceeds the critical strain value.

All these events can happen in both temporally or spatially localized or distributed manner. As a result, following the quench, the transport current gets shared or completely diverted to the stabilizer matrix. This leads to Joule heating of the superconductor. The resistive region grows and this is known as 'normal zone growth'. Associated with the normal zone growth, heating occurs till the transport current is diverted through an external circuit and the load is bypassed from the power supply. The uncontrolled heating can lead to serious thermal stresses within the winding pack of the high-T_c superconductor. Thus, the temperature rise is the most significant observation in a quench event. In practical applications, reducing the thermal stress by quickly spreading the temperature uniformly all over the superconductor is always desirable. Thus, the information on the temperature profile evolution across the ends of the superconductor is always an important parameter. In fact, in practical applications such as in large superconducting magnets, the temperature on the superconductor is often measured and monitored.

The motivation for the present work is the desire that all important temperature profile evolutions must be predicted and determined in any high-T_c-based practical applications. These predictions can be used as important design tools for the practical realization of high-T_c-based applications. With the prior knowledge of the temperature characteristics of the high-T_c-based applications, both the cryogenic stability as well as the 'protection' aspects of the applications can be appropriately enhanced. Section 2 discusses in detail the mathematical formulation whereas §3 describes the results and discussion.

2. Mathematical formulation

A thin HTS tape of finite length L is considered for analysis as shown in figure 1. Due to very slow local normal zone propagation of the order of mm/s in case of HTS [10], the heat generated along the length of the superconductor results in temperature gradients at different positions with respect to time.

The normal-zone propagation process in a superconductor is governed by a one-dimensional heat balance equation, which can be written as

$$\rho C_{\mathrm{p}}(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left\{K(T)\frac{\partial T}{\partial x}\right\} + q(T) - w(T), \tag{1}$$

where ρ is the mass density of the tape, $C_{\mathrm{p}}(T)$ is the specific heat, $K(T)$ is the thermal conductivity, $q(T)$ is the rate of heat generation due to Joule heating and $w(T)$ is the rate

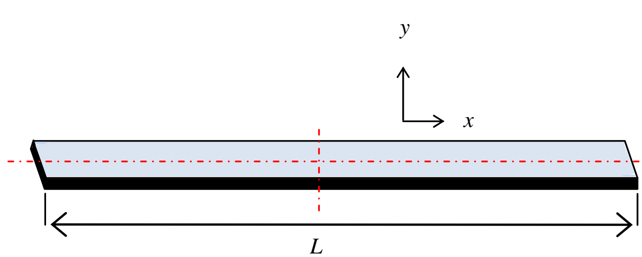

Figure 1. Schematic diagram of YBCO thin tape of finite length.

of heat transfer. In our case, the boundary conditions $T(0, t) = T_i$, $T(L, t) = T_i$ and $T(x, 0) = T_i$ will govern the heat balance equation (1). Equation (1) can be solved by applying the method of separation of variables as

$$T(x, t) = \Psi(x, t) + \phi(x) \tag{2}$$

so that

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\mathrm{d}^2 \phi}{\mathrm{d}x^2} + \frac{q'}{\lambda} = \frac{1}{\lambda}\frac{\partial \Psi}{\partial t}, \tag{3}$$

where $\lambda = K(T)/\rho C_{\mathrm{p}}(T)$ is the thermal diffusivity of the tape and $q' = [q(T) - w(T)]/\rho C_{\mathrm{p}}(T)$.

Equation (3) can be split into two parts such that

$$\frac{\partial^2 \Psi}{\partial x^2} = \frac{1}{\lambda}\frac{\partial \Psi}{\partial t} \tag{4}$$

and

$$\frac{\mathrm{d}^2 \phi}{\mathrm{d}x^2} + \frac{q'}{\lambda} = 0. \tag{5}$$

Equations (4) and (5) can be solved in a similar way as above by applying the method of separation of variables and equating with a reciprocal of negative separation constant $(-1/\alpha^2)$. In order to have finite solutions for all the values of time, we have the general solution as

$$\Psi(x, t) = \mathrm{e}^{-\lambda t/\alpha^2}\left[D\cos\left(\frac{x}{\alpha}\right) + E\sin\left(\frac{x}{\alpha}\right)\right] \tag{6}$$

and

$$\phi(x) = -\frac{q'}{2\lambda}x^2 + F_1 x + F_2, \tag{7}$$

where D, E, F_1 and F_2 are unknown constants. On substituting the initial condition to eq. (2), we obtain

$$\Psi(0, t) + \phi(0) = T_i \ \text{ and } \ (L, t) + \phi(L) = T_i.$$

Let

$$\Psi(0, t) = 0 \ \text{ and } \ \Psi(L, t) = 0 \tag{8}$$

so that

$$\phi(0) = T_i \ \text{ and } \ \phi(L) = T_i \tag{9}$$

and

$$\Psi(x, 0) = T_i - \phi(x). \tag{10}$$

Under the boundary condition as stated above, eq. (6) will yield

$$D = 0 \ \text{ and } \ \sin(L/\alpha) = 0 \Rightarrow \alpha = L/n\pi, \quad n = 1, 2, 3 \ldots.$$

Thus, eq. (6) reduces to a general equation given by

$$\Psi(x, t) = \sum_{n=1}^{\infty} E_n \sin\left(\frac{n\pi x}{L}\right)\mathrm{e}^{-\lambda(n\pi/L)^2 t}, \tag{11}$$

where n is a +ve integer.

Similarly, the other boundary conditions will give $F_2 = T_i$ and $F_1 = q'L/2\lambda$ so that eq. (7) can be written as

$$\phi(x) = T_i + \frac{q'}{2\lambda}(L - x)x. \tag{12}$$

Again from eqs (10) and (11), we obtain

$$T_i - \phi(x) = \sum_{n=1}^{\infty} E_n \sin\left(\frac{n\pi x}{L}\right). \tag{13}$$

Multiplying both sides of eq. (13) with $\sin(m\pi x/L)$ and integrating from 0 to L and then substituting the value of $\phi(x)$, the constants E_n can be obtained as

$$E_n = -\frac{2q'L^2}{\lambda}\left[\frac{1-(-1)^n}{(n\pi)^3}\right]. \tag{14}$$

Thus the temperature at different portions of HTS tape for given heat load can be represented as

$$T(x,t) = T_i + \frac{q'}{2\lambda}(L - x)x + \frac{2q'L^2}{\lambda}\sum_{n=1}^{\infty}\left[\frac{(-1)^n - 1}{(n\pi)^3}\right]\sin\left(\frac{n\pi x}{L}\right)e^{-\lambda(n\pi/L)^2 t}. \tag{15}$$

This temperature profile $T(x,\ t)$ represents the temperature variation along the entire length of the tape for a given time. Also it represents the temperature variation at a given point as a function of time.

3. Results and discussion

Yttrium barium copper oxide (YBCO) tape [11] of 100 mm × 4 mm × 0.2 mm dimension with a superconducting film of 0.8 μm thickness at an initial temperature of 80 K has been considered. Since the specific heat and thermal conductivity of this tape are temperature-dependent, the averages of these variables are considered for the analysis. From the temperature profile expression, it is evident that over the temperature range of interest, the averaged value is a good approximation. The averaged values of thermal conductivity $\langle K(T)\rangle$ and specific heat $\langle C_p(T)\rangle$ of the YBCO tape are taken as 2.93 W/m·K and 191.83 J/kg·K respectively. The composite density of the tape is taken as 6300 kg/m^3. A heat generation of 10 W/cm^3 has been considered and $T(x,\ t)$ is plotted with respect to time as a function of axial length x using MATLAB program. The results are shown in figure 2.

From the above results, it is evident that both edges of the tape get saturated rapidly for each of the time period. The temperature remains steady throughout the length of the tape. Also it is observed that as the time increases, the temperature of HTS also increases. All these observations are in accordance with physical observations of edge-cooled high-temperature superconductors. The temperature plateau indicates that the hot spot is centred and an efficient heat extraction from the interior of the tape is required

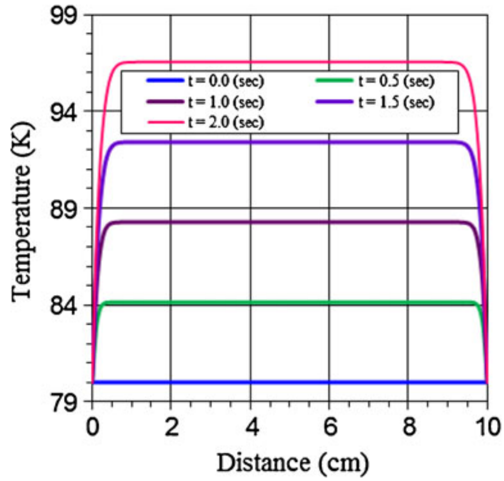

Figure 2. Temperature of YBCO tape with respect to the position coordinate for different times.

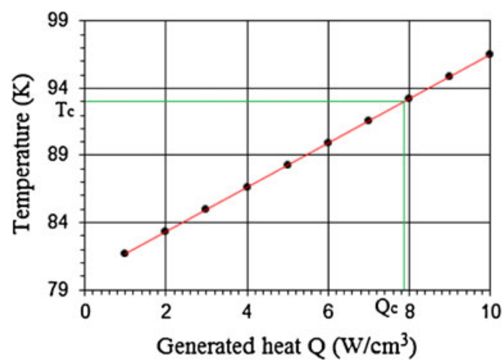

Figure 3. Temperature along the length of YBCO tape for different heat generation for a given time period of $t = 2.0$ s, excluding both the edges.

as a necessary cryostability criterion. This also supports the fact that more is the wetted perimeter the better is the heat transfer and more stable is the superconductor in applications.

Next, for a given time period, different heat generation is applied to the tape. The rise in the temperature of the tape at selected locations was computed. The optimum amount of energy required to just raise the temperature of the HTS above its critical temperature was then determined. This energy input is often referred to as the 'minimum quench energy' of the superconductor. In all practical applications, the disturbance energy must be less than this energy, otherwise an irreversible normal zone would appear and the tape would be quenched. Figure 3 shows the rise in temperatures against the given input energies. It is evident that for given fixed boundary conditions and for a fixed heat transfer coefficient, the rise in temperature is proportional to the heat input. The critical temperature 93 K is reached when the heat generation is $\sim$8 W/cm^3 for the time period of 2.0 s. The critical disturbance for this particular tape is roughly 12.8 J/m while for its superconducting section it is 0.0512 J/m.

4. Conclusion

In practical applications, spatial and temporal disturbances are inevitable. The magnitude of the disturbance leading to the quench of edge-cooled HTS has been investigated here. The state-of-the-art high-temperature YBCO superconductor has been computed to have a threshold quench energy of 12.8 J/m for the overall tape while for its superconducting section, it is 0.0512 J/m. Thus, in all applications, care must be taken to limit the disturbance energy to a value less than 12.8 J/m for the stable operation of the superconductor. Following a quench, the superconductor is also required to be protected from overheating. The quench-induced maximum temperature rise as well as the rate of rise in the region of initiation of quench popularly known as the 'hot spot' thermally stress the HTS cable. It can be reduced with better cooling and lowering the nominal transport current in the HTS cable. The maximum hot spot temperature for heat inputs in excess of the minimum quench energy has been analysed from first principles. In such cases, it is observed that the centre of the tape attains hot spot temperature over a broad width. The maximum temperature increases with the value of heat input and eventually an irreversible break-down of cooling against the Joule heat generation occurs. For a cryostable operation of HTS, the wetted perimeter of the tape may be increased enabling enhanced extraction of heat.

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