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Heat conduction and thermal stabilization in YBCO tape

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Abstract. **Yttrium barium copper oxide (YBCO) coated conductors are widely used in the conduction-cooled superconducting magnets with rapid development in refrigeration technologies at present. 'Quench' is a state that refers to the irreversible and uncontrolled superconductor to resistive transitions in the superconductor. The propagation of 'quench' or 'normal zone' has different characteristics in these high temperature superconductors (HTS) compared to low temperature superconductors. The superconductor to normal index, known as '*n*' is much flatter in HTS. The hot spot emerging in local region due to quench and non-uniform critical current may cause permanent damage to whole HTS tape and hence the magnet winding pack. Thus it is necessary to determine the temperature profile along the length of HTS tape under a given energy (joule heating) such that propagation of the hot spot developed locally can be prevented early. In this study, a one dimensional, time dependent heat diffusion equation with appropriate boundary conditions are used to describe the consequences of the normal zone propagation resulting in the temperature diffusion in a HTS tape. The results demonstrate the necessity of adequate cooling of the edges of the flat HTS tapes to prevent irreversible normal zone transitions.**

Keywords. **YBCO; conduction-cooled; quench; hot spot.**

1. Introduction

Yttrium barium copper oxide (YBCO) based $2G/3G$ technical superconductors have emerged as one of the strongest candidates for several practical applications especially in the area of power utilities (Rupich *et al* 2004; Buck *et al* 2007; Malozemoff *et al* 2008; Li *et al* 2009; Ueda *et al* 2010). In most of these practical applications, the tape is either bath cooled or forced flow cooled (Chang *et al* 2003; Iwasa *et al* 2003) in nitrogen environment in the normal operational scenarios. In some of the cases, the superconductor winding pack is also conduction cooled with cryocoolers (Yoshida *et al* 2008) or in case of cryogen free applications. In case of off-normal scenarios, these superconductors do exceed in an irreversible fashion at the critical temperature, where usually the coolant is quickly expelled out and the superconductor becomes dry. Such a case is usually referred to as 'quench' of the superconductor. In such scenarios, the worst case prediction is best described by carrying out a thermal conduction of the initial quench zone (IQZ) over the superconductor. Following a quench, temperature of the winding pack at the region where the quench has initiated rises rapidly as a result of joule heating. This rise of temperature is uncontrolled which can induce unacceptable thermal stresses within the winding packs irrespective of whether the winding pack is actively or passively protected. Thus, it is imperative to learn the maximum temperature as well as the resulting temperature distribution in the superconductor following a quench. This maximum temperature is also of engineering importance and is known as 'hot spot' temperature. The rate of rise of temperature in addition to the hot spot temperature is very important since superconductor gets influenced by proportional thermal stresses. This stress, in specific cases can also degrade the subsequent current carrying capability of the superconductor.

In this direction, a theoretical investigation has been made considering an IQZ of the dried out technical YBCO superconductor, where the normal zone propagation mechanism is overwhelmingly dominated by instantaneous conduction of heat in the volume of superconductor following quench. The problem along with the assumption has been formulated in §2 followed by the results and discussion in §3.

2. Analyses

A thin YBCO tape of finite length 'L' has been considered. Under circumstances when cryostability is irreversibly violated following energy input exceeding the minimum quench energy, heating occurs. This heat pulse predominantly propagates along the length of superconductor. This heat propagation results in an evolving temperature profiles at different positions along the length and width of the tape as a function of time. In this analysis, it is assumed that the temperature does not vary along thickness of the tape. This is an

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isotropic assumption justified in almost all practical cases since the tape width is negligibly small compared to its length as shown in figure 1. The temperature $T(x,t)$ at position, x and time, t, can be represented by 1-D thermal diffusion equation governed by

$$\rho C_{\mathrm{p}}(T)\frac{\partial T}{dt}=\frac{\partial}{\partial x}\left\{K(T)\frac{\partial T}{\partial x}\right\},$$
$$\text{for } 0\le x\le L \text{ and } t\ge 0, \tag{1}$$

where ρ is the mass density of the tape in kg/m^3, $C_{\mathrm{p}}(T)$ the specific heat in J/kgK and $K(T)$ the thermal conductivity, W/mK.

Equation (1) can be solved by applying the method of separation of variables

$$T(x,t)=U(x)V(t), \tag{2}$$

so that

$$\frac{1}{\lambda}\frac{1}{V}\frac{dV}{dt}=\frac{1}{U}\frac{d^2U}{dx^2}, \tag{3}$$

where $\lambda = K(T)/\rho C_{\mathrm{p}}(T)$ is the thermal diffusivity of the tape in m^2/s.

Both sides of (3) is equated with a reciprocal of negative separation constant (α), so that a finite solution is obtained for all times. Thus, the general equation presented in (2) will take the form

$$T(x,t)=e^{-\lambda t/\alpha^2}\left[D\cos\left(\frac{x}{\alpha}\right)+E\sin\left(\frac{x}{\alpha}\right)\right]. \tag{4}$$

Appling the thermally insulated boundary conditions $T(0,t)=0$ and $T(L,t)=0$, (4) reduces to

$$T_n(x,t)=E_n\sin\left(\frac{n\pi x}{L}\right)e^{-\lambda(n\pi/L)^2t}, \tag{5}$$

where n is a +ve integer.

Thus, the general equation for the temperature profile can be written as

$$T(x,t)=\sum_{n=1}^{\infty}E_n\sin\left(\frac{n\pi x}{L}\right)e^{-\lambda(n\pi/L)^2t}. \tag{6}$$

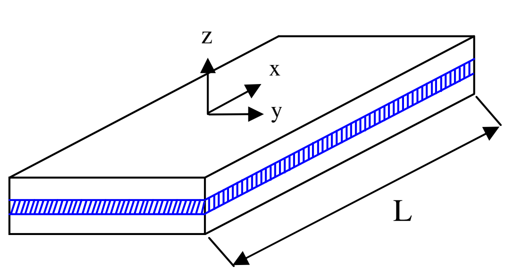

Figure 1. Schematic diagram of YBCO thin tape of finite length.

For $t=0$, (6) reduces to

$$T(x,0)=\sum_{n=1}^{\infty}E_n\sin\left(\frac{n\pi x}{L}\right). \tag{7}$$

For normalization purpose, multiplying both sides of (7) with $\sin(n\pi x/L)$ and integrating over the length of the tape, i.e. 0 to L, we obtain

$$E_n=\frac{2}{L}\int_0^L\sin\left(\frac{n\pi x}{L}\right)T(x,0)\mathrm{d}x. \tag{8}$$

Considering the temperature to be uniform all along the length before cryo-instability, i.e. at its beginning when $t=0$, we have $T(x,0)=T_0$, i.e. a constant throughout the tape. Thus,

$$E_n=\frac{2T_0}{n\pi}\left[1-\cos(n\pi)\right]. \tag{9}$$

The temperature at different portions of YBCO tape after the violation of cryostability without further cool down (adiabatic heating) can thus be represented by

$$T(x,t)=\sum_{n=1}^{\infty}\frac{2T_0}{n\pi}\left[1-\cos(n\pi)\right]\times\sin\left(\frac{n\pi x}{L}\right)e^{-\lambda(n\pi/L)^2t}. \tag{10}$$

This temperature profile, $T(x,t)$, represents the temperature variation along the entire lengths of the tape for a given time. Also it represents the temperature variation of a given co-ordinate with respect to time variation.

3. Results and discussion

An initial temperature of 80 K throughout YBCO tape (Fleshler *et al* 2009) of a finite length of 10 cm is considered. Since the specific heat and thermal conductivity of this tape are temperature dependent, $T(x,t)$ is plotted taking average

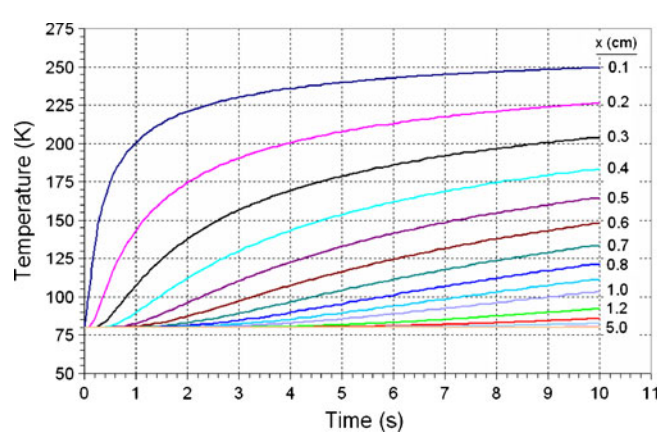

Figure 2. Temperature with respect to different times at different positions of HTS tape.

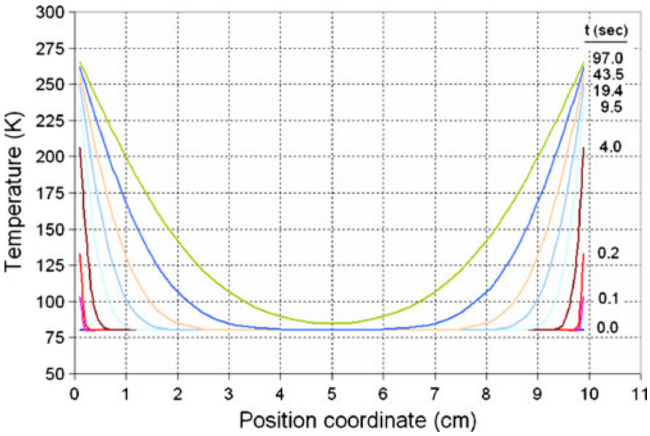

Figure 3. Temperature with respect to different coordinates at different times of HTS tape.

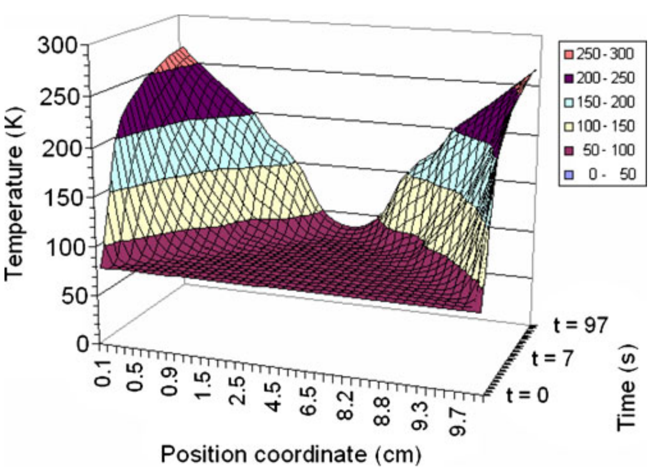

Figure 4. 3D representation of YBCO tape temperature distribution with respect to position coordinates and time.

of these variables using a MATLAB program with respect to time as a function of length 'x' as shown in figure 2.

It demonstrates that the middle of the tape remains stable while the temperature increases in either direction as a standing wave. The temperature rise begins at both the ends and rises very fast with time while stability persists for longer duration at the centre as shown in figure 3. It is also observed that as time span increases, temperature also increases in a corresponding manner.

The temperature at $x = 0{\cdot}1$ and 9·9 rises from 80 K to 85·5 K after 50 ms while the temperature at $x = 5$ rises from 80 K to 85 K after 97 s. This shows that the temperature remains most stable at the centre and very unstable at the edges as expected trying to equilibrate for a given heat input. This temperature instability moves towards the centre as time increases which is also represented through a 3D view as shown in figure 4.

4. Conclusions

The thermal stability of YBCO tape is represented numerically. It shows that the tape edges are necessarily to be adequately cooled so that hot spot developed locally by any non-uniformity of transport current can be prevented and hence quench can be avoided. Further this numerical analysis will be validated in laboratory also.

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References

Buck J, Hartman B, Ricket G, Gamble B, MacDonald T and Snitchler G 2007 *Factory testing of a 36·5 MW high temperature superconducting propulsion motor, Proceeding of the American Society of Naval Engineers (ASNE) Symposium, June 25–26, 2007*

Chang H M, Choi Y S, Van Sciver S W and Choi K D 2003 *Cryogenics* **43** 589

Fleshler S *et al* 2009 *Physica C* **469** 1316

Iwasa Yukikazu 2003 *Cryogenics* **43** 303

Li X *et al* 2009 *IEEE Trans. Appl. Supercond.* **19** 3231

Malozemoff A P *et al* 2008 *Supercond. Sci. Technol.* **21** 1

Rupich M W *et al* 2004 *Physica C* **412–414** 877

Ueda Xudong Wang, Ishiyama H, Yagi A, Saitoh M, Aoki T and Fujiwara Y 2010 *IEEE Trans. Appl. Supercond.* **20** 1268

Yoshida K *et al* 2008 *IEEE Trans. Appl. Supercond.* **18** 441