Hydraulic Quench Simulations in SSC Dipole Magnets

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Abstract

Anomalously high quench velocities have been observed in long 40mm aperture SSC dipole magnets. The thermal conduction mechanism does not properly explain the observed quench velocities in long SSC dipole magnets. A helium hydraulic event within the insulated conductor provides a plausible explanation for observed velocities. Preliminary results of a coupled thermal conductive and hydraulic numerical model of a conductor quench event produce velocities comparable to observations. The normal operating conditions are force-flow cooling at four atmospheres and 4.35 K temperature. The model quench velocities are dependent upon ambient pressure and slow down under pool boiling conditions. Slower pool boiling velocities in the model do not explain observations in short SSC dipole test magnets which are operated at pool boiling conditions.

I. Model

Recently, there have been several calculations of quench velocities using a helium hydraulic mechanism as the driving term in the time evolution of a quench event.[1-3] Primarily this hydraulic mechanism has been applied to conductor-in-conduit superconducting magnets. The 40mm aperture 17m SSC dipole magnets experience quench velocities which cannot be explained by thermal conduction models. An analytic model was developed which suggested that an annular helium expulsion model could explain the observed velocities.[4] This model may provide an explanation for the intractable events occurring beyond 80 milliseconds, but it does not explain the fast quench velocities seen closer to the inception of a quench event.

As an outcome of the annular model, there was speculation that there was a conduit within the Rutherford cable surrounded by a porous boundary of kapton, fiberglass, and epoxy. In an attempt to model an interstitial quench event, a coupled thermal conduction and thermal hydraulic model was developed using a predictor-corrector numerical technique. In this paper, results from this model will be presented.

The model consists of a coupled solution of heat generation and thermal conduction within the cable and a hydraulic representation of interstitial helium by heat transfer. The helium continuity, momentum, and energy balance equations are

$$\frac{\partial\rho}{\partial t} = -\frac{\partial\rho v}{\partial x} \tag{1}$$

$$\frac{\rho\partial v}{\partial t} = -\frac{v\partial\rho}{\partial t} - \frac{v\partial\rho v^2}{\partial x} - \frac{\partial p}{\partial x} - \frac{f\rho v^2}{2d_h} \tag{2}$$

$$\frac{\rho\partial u}{\partial t} = -(u+\frac{v}{2})\frac{\partial\rho}{\partial t} - \rho v\frac{\partial v}{\partial t} - \frac{\partial}{\partial x}(\rho v[u+\frac{v^2}{2}]+pv)+Q/A_{He} \tag{3}$$

and the cable thermal conduction equation is

$$\gamma CA\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\frac{kA\partial\theta}{\partial x} + \rho J^2 A + QA. \tag{4}$$

The hydraulic solutions are time advanced using predictor-corrector techniques. The conductor thermal conduction is time advanced with an Euler technique. All dependent thermodynamic state functions are computed using a package subroutine.[5]

Some approximation must be made for hydraulic properties of the area within the twisted wire cable. It is not clear that a continuous path exists within the cable. An estimate of the hydraulic diameter is $d_f = 10^{-4}$ m and the friction factor is assumed to be $f = 0.08$ which is somewhere between the laminar and turbulent flow regimes. Estimates of the hydraulic diameter are based on micrographs of collared conductors. The heat transfer rate between the helium and the conductor is approximated as $h = 1\times10^3\ J/m^2-K$ for 4 atm and $h = 3\times10^3\ J/m^2-K$ for pool boiling conditions. The heat transfer rate is $Q = hP(\theta_{Cu} - \theta_{He})$ where P is the wetted perimeter. It would be appropriate to add a transient approximation for heat transfer and future plans include this addition to the model.

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II. Results

In figure 1, the forced flow calculations at 4 atm are presented with long magnet data, the DD series magnets.[6] The results are similar to 40mm aperture long collider magnet data. The combination of hydraulic diameter and friction factor can be considered as a tunable parameter since there is inadequate information to evaluate these model parameters. As mentioned previously, values were specified with the best information available. The heat transfer coefficient is also poorly defined parameter for this transient model, but only generates a velocity offset with little effect on the non-linear behavior as seen in the two model cases with different h values.

Near short sample quench velocities are higher in the forced flow conditions regardless of the heat transfer rate. The pool boiling velocities are slower due to latent heat, but are not significantly slower. Additional models for sub-critical flow at 1.5 atm were performed and these results were identical to the pool boiling results. An experiment for a test magnet DD0012 was conducted at 1.5 atm and there was no significant difference in the short sample quench velocities between 1.5 and 4 atm. The primary difference between supercritical and subcritical helium models is that the supercritical velocities are much more non-linear as a function of fraction of short sample current. No experimental evidence is currently available to confirm this prediction.

The models presented in this paper do not completely describe the velocities observed in short magnets. Short sample quenches in these magnets are approximately 70 m/s.[7] A possible explanation is that quench velocities accelerate significantly in the first 1-3 milliseconds and the entire data aquisition period is on the order of 10 msec. The observed velocity is an average during this period and is lower than the peak velocity.

Further analysis of the quench temperature profile near wavefront reveals that a stationary state is formed after an acceleration period. This is a coupled state where the "hot helium" extending beyond the wavefront preheats the conductor as seen in figure 2. If the thermal conductivity term is eliminated, a quench velocity at $I/I_{ss} = 0.9$ would drop to approximately 3 m/sec. Standard thermal conduction models predict approximately 25-30 m/sec depending of heat transfer rates to the helium "bath". It is a combination of thermal conduction and preheating of the superconductor beyond the wavefront which develops that large quench velocities.

This probably would not be considered to be a "hydraulic quench back" as predicted for conductor-in-conduit energy storage magnets. It is rather an extra heat transfer term advancing the thermal conduction propagation. The spacial region involved in this propagation is on the order of 5 cm. It is likely that the hydraulic mechanism would need to act within a short distance due to a small hydraulic diameter.

This hydraulic model provides a feasible explanation for the fast quench velocities observed in SSC dipole magnets under different cryogenic conditions. There are several issues which are unresolved in this mechanism. The heat transfer outside the conductor is omitted. The conduit for Rutherford cable is porous and would relieve pressure. Both of these effects would slow down quench propagation. Presently, there is a long sample test in progress which could demonstrate the change in quench velocities due to varying cryogenic conditions and without a helium bath. This test should provide evidence to support or refute hydraulic mechanisms.

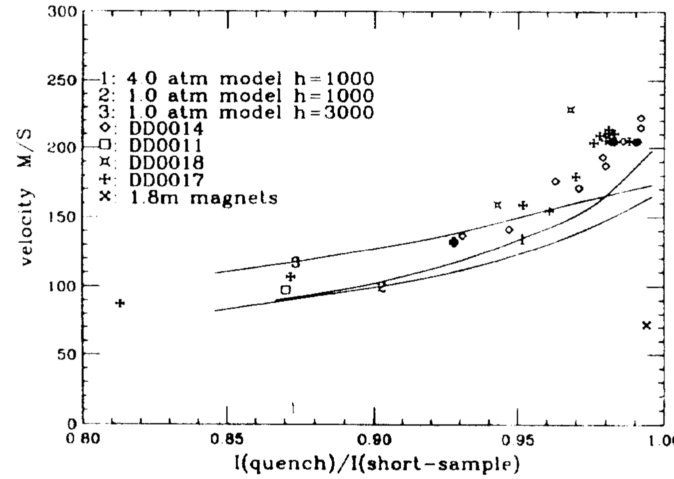

Figure 1 - Axial quench velocities

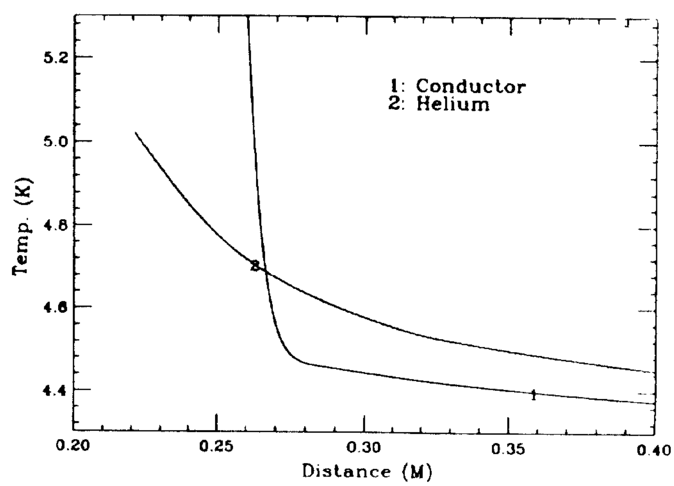

Figure 2 - Axial quench temperature wavefront profile.

In any case, the primary purpose for determining the quench propagation mechanism is to insure that future modifications to conductor and insulation design do not change the fast longitudinal velocities which help protect the SSC dipole magnets. A very porous insulation would significantly reduce the quench velocities.

References

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