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SIMULATION OF THE QUENCHING OF AN INTERNALLY COOLED SUPERCONDUCTING MAGNET*

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Stability measurements on cable-in-conduit internally cooled superconductors have shown that the heat transferred to helium earlier will cause a pressure rise and induce a transient flow inside the conduit. In turn, this will enhance the heat transfer and help the superconductor to recover to its superconducting state. However, if the heat input is very high or if the heated length is very long, the pressure rise can be tremendous and the helium expulsion can be excessive. This paper describes the experimental results of simulating the quench of an entire hydraulic path. The measured thermal expulsion of helium and peak pressure during the quench are compared favorably with a similarity theory and a simple scaling relation.

INTRODUCTION

When a section of an Internally Cooled Superconducting (ICS) magnet goes normal, the pressure inside the cooling passage rises rapidly and helium is expelled out of the heated zone. This can be particularly dramatic when the cable-in-conduit conductor is used because of the typically small hydraulic diameter of the flow path in such a conductor. The safety of the coil depends on the pressure rise in the worst case, which we take to be the instantaneous quench of an entire flow path. Aside from the immediate problem of containment of high pressures in the winding, the rapid expulsion of the helium from the quenching magnet also poses a potential danger for the helium header, piping, and refrigerator components. We have carried out an experiment to simulate such a quenching condition and to measure the peak pressure and helium efflux developed during a quench. This was augmented by a separate experiment that heated only a short section of an ICS and measured the propagation of its normal front.

EXPERIMENTAL SETUP

A 69-m-long copper-strand cable enclosed in a stainless steel sheath was constructed for the quench simulation study. A blocking valve was located at the inlet of the conductor that could be closed from the top of the cryostat. Closing of this valve simulates a quenching conductor of twice the length. The conductor was instrumented to measure the pressure rise along its length and the helium efflux at its outlet. Details of the conductor construction and instrumentation setup as well as some maximum quench pressure measurements have been reported earlier [1].

Normal zone propagation in an ICS was measured on a 5-m-long, NbTi single triplex. Its heater and voltage measuring arrangement have also been reported elsewhere [2].

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MASTER

EXPERIMENTAL RESULTS

The rapid heatup simulating a quench was accomplished by applying a square-wave current to the copper cable. The typical time evolution of the helium expulsion velocity and the pressure rises following the application of a heating current is shown in Fig. 1. In this example, a heating current of 760 A was applied for about 6.7 s.

The helium expulsion velocity rose rapidly at the onset of heating and reached a peak value in about 2.5 s. It started to come down even though the heating was still on. The pressure near the center of the conductor also rose rapidly. Though its rise rate had been slowed down quite a bit, it continued to rise beyond the heat pulse. The pressure at the outlet was intended to be constant to simplify analysis; yet, it showed a few atmosphere rise due to the pressure drop experienced at the relief valve and piping.

Figure 2 shows the helium thermal expulsion velocity evolution at different heating currents. The conductor matrix current density amounts to 15 kA/cm^2 at $I = 1250 \text{ A}$. This is to be compared to 13 kA/cm^2 at 16 kA for the Westinghouse Large Coil Program (LCP) coil [3]. A peak velocity of 42 m/s was observed in about 1.9 s after the heating started. The time to peak velocity was found to be roughly inversely proportional to the current. After the peak, the velocity generally dropped even more rapidly.

Measurements of the maximum pressure rise during a quench were extended to include the operating condition of the Westinghouse LCP coil. Figure 3 shows the pressure excursion near the center of the conductor at several different currents. This plot shows that at a half-quenching length $l = 34.5 \text{ m}$ it took about 4 s to reach a peak pressure. At $l = 69 \text{ m}$, it took more than 7 s to reach the peak. Therefore, a lot of the maximum pressures measured were not peak pressures.

The normal zone propagation data of a single triplex ICS are shown in Fig. 4. The superconductor was heated beyond its stability margin for a length of 0.53 m . The propagation of its normal zone down the conductor was measured. Propagation velocities in the range of $0.3\text{--}1.6 \text{ m/s}$ were observed at a magnetic field of 7.0 T .

DISCUSSION

Dresner [4] has developed a similarity theory for the thermal expulsion of helium from a quenching ICS. Based on the assumptions of (1) the inertial force on a fluid element $\ll$ the frictional force on a fluid element, (2) constant thermophysical properties, (3) the rarefaction wave moving inwards from the ends having not reached the center, (4) Joule heating $\gg$ heating due to mechanical energy being converted into heat by friction ($\dot{q} \gg 2fv^3/D_h$), and (5) no pressure rise at the outlet, the similarity solution gives

$$v \cdot t^{1/3} = 0.952 \left(\frac{\beta c}{C_p} \right)^{2/3} \left(\frac{D_h}{f} \right)^{1/3} \cdot (\dot{q} t)^{2/3}. \quad (1)$$

Instead of $\dot{q} t$, $I^2 t$ is more convenient, and Fig. 5 shows the data taken from Fig. 2 in such a plot. Within 1 s most of the assumptions made in the similarity theory should be all right. It is, however, possible to correct the similarity solution for heat production by the conversion of mechanical energy into heat by making the replacement

$$\dot{q} \rightarrow \dot{q} + \frac{2fv^3}{D_h} \left(1 + \frac{C_p}{\beta c^2} \right). \quad (2)$$

This procedure should be all right as long as the second term is small in comparison with the first. It cannot be used generally because $\dot{q}$ and v^3 are distributed spatially in a much different way. The corrected similarity theory is shown as a dashed line for $I^2t < 10^5 \text{ A}^2\text{s}$. It appears to be in the right direction of reducing the discrepancy.

Our simple theory [1] for the peak pressure during the quench of an ICS magnet showed that the peak pressure scales as

$$p_{\max} \propto \chi^{0.36}, \quad \chi = \frac{Q^2 \ell^3}{D_h} \quad (3)$$

The measured maximum pressures from data like Fig. 3 are plotted versus the scaling parameter χ in Fig. 6. The data point with an arrow sign (+) indicates that the maximum pressure measured is not a peak value yet. The two straight lines from the simple theory are for a smooth tube friction factor of $f = 0.0044$ and for a factor of 3 higher of $f = 0.013$ as was measured [5] in cable-in-conduit conductors like the one used in the present experiment. The present data seem to confirm both the simple theory for peak pressure and the friction factor data.

The normal zone propagation data shown in Fig. 4 were taken on a relatively short sample. Most of the assumptions that the similarity theory was based on were not met in this case. Therefore, this result cannot be compared with the solution similar to Eq. (1). However, a curve drawn through the data point at $I = 200 \text{ A}$ indicates that the normal zone propagation velocity is also roughly proportional to $\dot{q}^{2/3}$. For comparison, the normal zone propagation and recovery velocity of this superconducting triplex in an open bath-cooled condition was also shown in Fig. 4. The vast difference between these two sets of data indicated that the normal zone propagation velocity of an ICS is faster than in open bath and is governed by the thermal expulsion rate of helium rather than the balance of heat transfer and heat conduction in the conductor. Furthermore, since the inventory of helium in an ICS is limited, it can always be heated hot enough for the normal zone to propagate. There is no minimum propagating or full recovery current in an ICS.

CONCLUSION

Simulation experiments on the quenching of an ICS magnet have led to a better understanding of the hydrodynamics of helium during a quench. We are satisfied with the fair comparison of the measured thermal expulsion velocity of helium to the similarity solution. The extended data on the peak pressure during a quench have confirmed the simple scaling relation developed earlier. Normal zone propagation data in an ICS showed a vastly different nature than in an open bath-cooled superconductor.

LIST OF SYMBOLS

- c = sonic velocity ($\text{m}\cdot\text{s}^{-1}$)
- C_p = specific heat ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
- D_h = hydraulic diameter (m)
- f = fanning friction factor
- I = conductor current (A)
- ℓ = half hydraulic length (m)
- p = absolute pressure (Pa)

$\dot{q}$ = heating rate per unit mass of helium ($\text{W}\cdot\text{kg}^{-1}$)

Q = heating rate per unit volume of helium ($\text{W}\cdot\text{m}^{-3}$)

t = time (s)

v = flow velocity ($\text{m}\cdot\text{s}^{-1}$)

χ = scaling parameter = $Q^2 l^3 / D_h$ ($\text{W}^2\cdot\text{m}^{-4}$)

β = volume coefficient of thermal expansion (K^{-1})

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Fig. 1. Time evolution of helium thermal expulsion and pressure rises

Fig. 2. Helium thermal expulsions as a function of conductor current

Fig. 3. Maximum pressure excursions as a function of conductor current

Fig. 5. Scaling of peak pressure vs $Q^2 L^3 / D_h$

Fig. 4. Scaling of $vt^{1/3}$ vs $I^2 t$

Fig. 6. Normal zone propagation of a single triplex internally cooled superconductor