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TITLE: ENHANCED HEAT TRANSFER COMPUTATIONS FOR INTERNALLY COOLED CABLE SUPERCONDUCTOR

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ENHANCED HEAT TRANSFER COMPUTATIONS FOR INTERNALLY COOLED CABLE SUPERCONDUCTOR

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Abstract

Superconducting magnets are built with conductors that are pool bath cooled, internally cooled with the superconductor cabled and contained within a conduit, or conduction cooled. The first two embody superconductors in direct contact with liquid helium. Practical designs of internally cooled cable superconductor (ICCS) are not cryostable. Such superconductors have shown multiple regions of stability and instability. A computational method of adjusting the heat transfer coefficient of a one dimensional system of equations to enhance joule heat removal, primarily in the central region of a pulse heated model of ICCS, has been used to attempt simulation of the multiple stability/instability experiment.

Introduction

Stability measurements on internally cooled cable superconductor (ICCS) by Lue, Miller, and Dresner[1] with additions of pulsed heat to drive the superconductor into its resistive state (normal) showed recovery to the superconducting state (stability) to have multivalued regions dependent upon magnetic field, current density, helium mass flow rate, and pressure. In that experiment, ambient temperature helium gas was introduced into the experiment through a heat exchanger system that provided liquid helium to the superconducting test section and the pulse heated extensions thereto. The exhaust helium was returned to ambient temperature by cooling the incoming helium through the counter flow heat exchanger. This experimental arrangement created a test section with appreciable volumes of compressible helium on both ends. Experiments[2,3,4] on saturated two-phase and super-critical hydrogen indicate that fluid compressibility and the end conditions of a test section are important features that affect pressure oscillations and heat transfer.

The experiment[1] showed pressure oscillations over time spans, not equated to acoustic pressure waves, such that alternating reversed and forward helium flow occurred to enhance heat transfer and stability under some conditions. Although dual instability regimes were observed at essentially zero flow velocity, the size of the lower instability regime decreases with increasing flow until it disappears at sufficiently high flow velocity. This is attributed to the augmented heat transfer and fluid heat capacity with increased flow that supplements any enhanced heat removal arising from bulk helium oscillatory flow at low flow rates.

Consideration of this behavior led to an inquiry about experiments with different end conditions. Miller[a] indicated that experiments conducted with the test section isolated at the ends did not show the dual instability. Thus, one might conclude that the phenomenon does indeed depend upon the end conditions and flow oscillations that are amplified by coupling to more compressible fluid regions not unlike the hydrogen experiments.[2,3,4]

Turner and Shindler[5] were able to simulate the multiple stability/instability regions of the Lue, Miller, Dresner experiment with a computer model that approximated that work. The heater length for the model was markedly shorter in the simulation to save computer time. The duration of the heat pulses was reduced to reproduce the multivalued regimes. The successful computer simulation was not realized if pressure oscillations were permitted to occur before the heat pulse was terminated. Both of these model variations from the experimental conditions may have produced a system unique to the calculation that was not actually characteristic of the experiment. Turner and Shindler also found that the successful simulation required highly asymmetric end conditions for the model and that symmetric end conditions thwarted the simulation. Whether or not the actual experiment was highly asymmetric is difficult to ascertain from the literature.[1]

Experiment and model

The physical parameters of the test section for the experiment are those of reference 1 and are listed in Table I. The model, used in this computational effort, attempts to accommodate the actual heated length of the real experiment, the same heat pulse energy and duration, and to permit pressure oscillations, as computed, to occur during the heat pulse duration. These conditions are listed in Table II. Figure 9 of reference 1 plots the heat pulse input to the conductor versus flow rate of the helium. The multivalued stability/instability regime exists from zero to about 0.15 g/s flow rate. For this work an intermediate value of 0.05 g/s was chosen for most

TABLE I
ICCS TEST SECTION

Superconductor	NbTi
Strand diameter, mm	1.00
Length, mm	3.25
Cu/NbTi	4.5
Sheath inside diameter, mm	2.41
Fluid fraction	0.52[a]
Conductor cross section, mm^2	$2.36\ (10)^{-6}$
Critical current, A at 7 T, 4.2 K	400

[a]Table I of reference 1 gives a value of 0.44 that is inconsistent with the strand and sheath dimensions except that the solder of the superconductor triplex probably accounts for the difference.

TABLE II

CONDITIONS FOR THE EXPERIMENT AND COMPUTATION

Current, A	400
Field, T	6.0
Helium inlet temperature, K	4.2
Helium inlet pressure, atm	5.0

[a]Information from J. R. Miller, Lawrence Livermore

of the calculations and the heat pulse input was used as the principal variable parameter of the computations.

Results

As for the calculations performed by Turner and Shindler, recovery from the normal conducting state did not occur when highly symmetrical heat transfer profiles existed about the center of the heated test section. A number of model changes were used for attempts to simulate the experimental multiple stability/instability observations. The lengths of the flow path were adjusted on the ends of the test section. These were treated as adiabatic flow channels. A limited urbalance to create a significant asymmetry had initially been investigated by reducing the exit flow impedance to reproduce the multiple phenomenon with no success. This approach was then extended to reduce the exit flow impedance greatly in a manner similar to the work of reference 5, again to no avail. For all cases, inherent in the one dimensional equations upon which the computer code is based,[6] the patterns remained highly symmetric with very low heat transfer at or near the center of the test section. Although pressure oscillations with related alterations of helium properties and conductor temperatures were observed to have been generated, the general pattern was first for a reduction in joule heating away from the central portion of the test section, then a narrow peaking of heat generation at the center, all followed by a runaway condition with increased heat generation and lengthening of the resistive zone.

The computer program[6] used in this work has options for modifying the heat transfer as a function of the velocity gradient. Because of the symmetry, the velocity at the center of the heated section reverses and goes through zero with the velocity dependent portion of the heat transfer coefficient going to zero. Arp[6,7] discusses the limitations of the one dimensional system of equations and suggests the use of a code option to enhance the heat transfer coefficient in the zero velocity region. This is accomplished by an additive term to the Reynolds number, used to calculate the heat transfer coefficient. The term contains the product of the velocity gradient, the Reynolds number, and an arbitrary multiplier available to the code user as an adjustable parameter.

The problem with the one dimensional treatment is that it cannot reproduce any turbulence or fluid mixing that certainly must occur throughout the contained conductor cable interstices. Although the term, added to the Reynolds number, does not remove the one dimensional nature of the analysis, nor eliminates the basic symmetrical heat pattern, it does accomplish an enhancement of the heat transfer coefficient in the regions where the velocity gradient is large. The parameter, the multiplier of the velocity gradient, was explored as an adjustable value in a number of computations to investigate the model with heated length and heat pulse energy and duration the same as for the real experiment[1] while allowing pressure oscillations to occur during the heat pulse.

Clearly, the computational manipulation used here is an artifice to ascertain the limitations of the one dimensional code and the implications of enhanced heat transfer where the velocity gradient is largest in regions where three dimensional effects would be expected to be pronounced. The definitive success of Turner and Shindler to simulate the multiple stability/instability regimes for conditions somewhat dissimilar to those of the experiment was not achieved here. A number of comparative results are presented in Table III with flow rate, heat input, and the multiplier used to enhance the heat transfer coefficient as parameters of the study.

The results are noted as having returned to the superconducting state, R=recovered, or not, NR=not recovered. The time designates the simulated real time lapse after initiation of the 7.14 ms duration heat pulse when recovery occurred. For the actual experiments,[1] recovery occurred in some cases after 70 to 140 ms. In every case for which recovery was indicated in the calculations, the periods were substantially less. Recovery to the superconducting state for a heat pulse of 40 mJ/cm^3 requires heat transfer enchancement with a Reynolds number multiple of 0.12. Sensitivity to the multiplier is low with the value increased to only 0.13 for recovery at 85 mJ/cm^3. At 102 mJ/cm^3 the value for recovery increased substantially to 0.18. At pulsed energy inputs of 128 and 171 mJ/cm^3 recovery was not observed, even with multipliers up to 0.30 and nearly doubled flow rates. Recovery at these heat levels would require even greater flow rates. The sensitivity between recovery and nonrecovery for pulsed energy inputs from 40 to 102 mJ/cm^3 was less

TABLE III

RESULTS OF ICCS CALCULATION ENHANCED HEAT TRANSFER
Heated length= 3.25 m, Heat pulse duration= 7.14 ms

Pulse Energy mJ/cm3	Velocity g/s	Reynolds No. Multiplier	Time To Recover, ms	R=recovered NR=not recovered
40	0.05	0.12	14	R
40	0.05	0.11	--	NR
65	0.05	0.12	16	R
66	0.05	0.12	—	NR
68	0.05	0.12	--	NR
68	0.06,0.09,0.13	0.12	—	NR
68	0.09	0.13	16	R
85	0.05	0.13	21	R
85	0.05	0.12	--	NR
102	0.05	0.18	16	R
102	0.05	0.17	—	NR
128	0.05	0.18 to 0.30	--	NR
171	0.05 to 0.09	0.13 to 0.25	--	NR

than 0.01, the incremental limit used in changing the multiplier. If smaller increments had been used, the calculation would converge on a precisely determined multiplier for the boundary condition between recovery and nonrecovery.

Comment

Many other calculations were performed. The unusual aspect of multiple stability for the conditions of Table II was not found. The present state of development of the available codes[6,8,9] for calculating the performance of ICCS is such that they have not been shown to simulate the results of experiments[1] when the inputs to the codes are like the test conditions of those experiments. The codes are essentially the same because the SSICC code incorporates the code of Arp[6] with modifications. The codes give useful trends in ICCS performance, can be made to simulate the multiple stability conditions if certain inputs are used in the calculations,[5] and can be used to infer information about the heat transfer performance required for recovery under some conditions, with such performance not fundamentally apparent in the one dimensional structure of the equations upon which the codes are built. As such, the codes are good diagnostic tools but should be used with caution for engineering design. For design purposes the empirical correlations of Lue and coworkers[10,11,12] should be used to avoid the multiple stability/instability regions.

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