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PROGRAM CICC FLOW AND HEAT TRANSFER IN
CABLE-IN-CONDUIT CONDUCTORS

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Abstract

Computer program CICC has been written for use in the thermo-fluids design of superconducting magnets for tokamak reactors, which use forced-flow, helium-cooled, cable-in-conduit conductors (CICC). In addition to background heat loads that vary with space and time, these superconductors can develop normal zones that generate electrical resistance heat. Program CICC models the transient thermodynamic and fluid-dynamic system response to background heating and normal-zone propagation in the superconductor. The computational algorithm described in this paper couples a one-dimensional, compressible pipe-flow model (including flow choking) with two-dimensional, axisymmetric heat-conduction models of the superconductor cable, the conduit, and the epoxy-conduit insulation. National Institute of Standards and Technology helium properties are used. The model is verified by comparison with measured temperature and pressure profiles from thermal expulsion experiments.

Introduction

One of the candidate conductor designs for superconducting magnets proposed for future tokamak reactors utilize magnets with forced-flow, helium-cooled cable-in-conduit conductors (CICC). The electrical heat generated when this conductor becomes normal is transferred to the helium coolant, causing the helium to heat rapidly. This causes high helium pressures inside the conductor, forcing the helium to flow in both directions away from the heated zone.

Program CICC

Program CICC simulates the helium-fluid-dynamic response as a transient one-dimensional, compressible flow. This flow model is combined with axisymmetric CICC conductor and insulation models (Fig. 1) and the equation of state for helium. [4].

Figure 1. Forced-flow-cooled conductor schematic.

The helium flow is described by three one-dimensional pipe-flow-conservation equations:

1. Helium momentum equation:

$$\frac{\partial(\rho u)}{\partial t} = -\frac{\partial}{\partial x}(p + \rho u^2) - \left(\frac{f}{d_h}\right)\left(\frac{1}{2}\rho u|u|\right) \quad (1)$$

The experimental friction-factor correlation from Lue, et al. [1,2] is used.

2. Helium continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0 \quad (2)$$

3. Helium energy equation:

$$\left(\frac{\partial}{\partial t}\right)\left[\rho\left(e + \frac{1}{2}u^2\right)\right] = -\frac{\partial}{\partial x}\left[(\rho u)\left(h + \frac{1}{2}u^2\right)\right] + \left(\frac{\partial}{\partial x}\right)\left[k\frac{\partial T}{\partial x}\right] + \frac{1}{A_c}\left[\frac{A_{ic}}{R_c}(T_c - T) + \frac{A_{tw}}{R_w}(T_w - T)\right] \quad (3)$$

The experimental, convective, heat-transfer correlation from Giarratano [3] is used.

All of the other CICC conductor components are solid. They are each described by an axisymmetric energy equation:

1. Conductor energy equation:

$$(\rho_c C_c)\left(\frac{\partial T_c}{\partial t}\right) = \frac{\partial}{\partial x}\left(k_c u k_c u \frac{\partial T_c}{\partial x}\right) + \frac{1}{A_{cc}}\left[\frac{A_{ic}}{R_c}(T_c - T) + (Q_{gen})\right] \quad (4)$$

2. Conduit-wall energy equation:

$$(\rho_w C_w)\left(\frac{\partial T_w}{\partial t}\right) = \frac{\partial}{\partial x}\left(k_w \frac{\partial T_w}{\partial x}\right) + \frac{1}{A_{cw}}\left[\frac{A_{tw}}{R_w}(T - T_w) + \frac{(A_{te})}{(R_e)_1}\left[(T_e)_1 - T_w\right]\right] \quad (5)$$

3. Epoxy-insulation energy equation for layer n:

$$(\rho_e C_e)\left[\frac{\partial (T_e)_n}{\partial t}\right] = \frac{\partial}{\partial x}\left[k_e \left(\frac{\partial (T_e)_n}{\partial x}\right)\right] + \frac{1}{(A_{ce})_n}\left[\frac{(A_{te})_n}{(R_e)_n}\left[(T_e)_{n-1} - (T_e)_n\right] + \frac{(A_{te})_{n+1}}{(R_e)_{n+1}}\left[(T_e)_{n+1} - (T_e)_n\right]\right] \quad (6)$$

The epoxy insulation is not a good conductor, so allowances are made for dividing the insulation thickness into multiple circumferential layers.

Equations 1 through 6 and the equation of state [4] are solved simultaneously by the method of lines. The spatial derivatives are approximated by the staggered-grid, finite

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differencing scheme shown in Fig. 2 [5]. The conservation elements for the continuity and energy equations are staggered relative to the elements for the momentum equation. This stabilizes the calculation for the pressure in the momentum equation. The resulting system of transient ordinary differential equations is then solved using DASSL [6].

Figure 2. Staggered grid in section of conductor.

Experimental Verification

Program CICC was verified by comparison with the results of thermal expulsion experiments of Lue and Miller, et al. [7,8]. Their experiments simulated a CICC conductor quenching over the entire length by constructing a conductor using copper wire in a conduit. The conductor is wound around a 10-mm-thick, PVC-pipe mandrel and placed inside a liquid-helium-cooled, cylindrical, stainless-steel dewar. There is about 1 mm of insulation between the coil turns and 4 mm of insulation between the coils and the dewar wall [7]. The CICC conductor was initially filled with stagnant helium. Current was then passed through the copper wire, heating it along the entire conductor length and expelling helium out of the open conductor ends. The experiments with the 69-m-long conductor were made with one end closed and with both ends open. In order to match the experimental boundary conditions using program CICC, the experimental geometry with one end of the 69-m-long conductor closed had to be modelled as a 138-m-long conductor with both ends open. The insulation is assumed to be 2-mm thick.

Figures 3-5 compare the calculated and experimental transient pressures at the middle of the conductor model for the geometry with one end closed ($L = 138$ m). Figures 6-8 compare the pressures at the middle of the conductor model for the geometry with both ends open ($L = 69$ m). The currents range from 760 A to 1540 A and have a square-wave-pulse shape that is on for the entire 7 seconds.

Figure 9 compares the calculated and experimental transient temperatures at the middle of the conductor for a case with both ends open and a current of 940 A.

The computed results agree with the measured values, considering the limitations of the axisymmetric heat-transfer model and the uncertainty in the values of the turbulent friction factor. The pressure represents the

Figure 3. Thermal Expulsion, 138-m, 760-A conductor middle He pressure.

Figure 4. Thermal Expulsion, 138-m, 1250-A conductor middle He pressure.

Figure 5. Thermal Expulsion, 138-m, 1540-A conductor middle He pressure.

results of a delicate balance between the radial heat loss out of the conductor and the friction pressure drop. The calculated pressures are higher than the experimental pressures for the runs with one end closed. The calculations are lower than the experimental pressures for the runs with both ends open. This indicates that the friction factor is low and that an additional unaccounted for heat conduction path exists between the two bifilar-wound conductor legs when one end is closed.

Figure 6. Thermal Expansion, 69-m, 760-A conductor middle He pressure.

Figure 7. Thermal Expansion, 69-m, 940-A conductor middle He pressure.

Figure 8. Thermal Expansion, 69-m, 1250-A conductor middle He pressure.

Conclusion

Program CICC has been written to solve the transient thermal-fluids problem of a forced-flow, helium-cooled CICC conductor going normal. The program can be used to determine the stability of a conductor to a given heating situation, or to determine the survivability of a conductor to a given quench situation. For further information about program CICC, see Refs. [9] and [10].

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Figure 9. Thermal Expansion, 69-m, 940-A conductor middle temperature.

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Nomenclature

A_c	= Cross-sectional area of He flow channel, m^2
A_{cc}	= Cross-sectional area of conductor, m^2
$(A_{ce})_n$	= Cross-sectional area of nth epoxy layer, m^2
A_{cw}	= Cross-sectional area of conduit wall, m^2
A_{tc}	= Convection heat-transfer perimeter for conductor, m
$(A_{te})_n$	= (n-1)th to nth epoxy-layer-interface perimeter, m
A_{tw}	= Convection heat-transfer perimeter for conduit wall, m
C_c	= Conductor heat capacity, $J/kg \cdot K$
C_{Cu}	= Conductor copper heat capacity, $J/kg \cdot K$
C_e	= Epoxy heat capacity, $J/kg \cdot K$
C_p	= He constant pressure heat capacity, $J/kg \cdot K$
C_{sc}	= Conductor superconductor heat capacity, $J/kg \cdot K$
C_w	= Conduit wall heat capacity, $J/kg \cdot K$
d_h	= Hydraulic diameter of He flow channel for friction, m. (Not used for heat-transfer perimeter.)
e	= He internal energy, J/kg
f	= Darcy friction factor based on d_h
f_{Cu}	= Volume fraction of copper in conductor
h	= He enthalpy, J/kg

h_c	= He convection heat-transfer coefficient, $W/m^2 \cdot K$
k	= He thermal conductivity, $W/m \cdot K$
k_{Cu}	= Conductor copper thermal conductivity, $W/m \cdot K$
k_e	= Epoxy thermal conductivity, $W/m \cdot K$
k_w	= Conduit wall thermal conductivity, $W/m \cdot K$
L	= x at conductor outlet end, m
p	= He pressure, Pa
Q_{gen}	= Conductor heat generation, W/m^3 of conductor
R_c	= Heat-transfer resistance between He flow and conductor, $m^2 \cdot K/W$
$(R_e)_n$	= Heat-conduction resistance between (n-1)th and nth epoxy layer, $m^2 \cdot K/W$
R_w	= Heat-transfer resistance between He flow and conduit wall, $m^2 \cdot K/W$
ρ	= He density, kg/m^3
ρ_c	= Conductor density, kg/m^3
ρ_{Cu}	= Conductor copper density, kg/m^3
ρ_e	= Epoxy density, kg/m^3
ρ_{sc}	= Conductor superconductor density, kg/m^3
ρ_w	= Conduit wall density, kg/m^3
t	= Time, s
T	= He temperature, K
T_c	= Conductor temperature, K
$(T_e)_n$	= nth epoxy layer temperature, K
$(T_e)_o$	= Epoxy outer surface temperature, K
T_w	= Conduit wall temperature, K
u	= He velocity, m/s
x	= Conductor length from inlet end, m