ABSTRACT

This report documents the computer programs CCAN (steady-state Compressible flow Conductor ANalysis) and TCAN (Time-dependent incompressible-flow Conductor ANalysis). These codes calculate temperature, pressure, power and other engineering quantities along the length of an actively-cooled electrical conductor. Present versions contain detailed property information for copper and aluminum conductors; and gaseous helium, liquid nitrogen and water coolants. CCAN and TCAN are available on the NMFEC4 CDC 7600.
List of Variables

A - area \((m^2)\)

B - magnetic field strength (Tesla)

c - specific heat at constant pressure \((J/kg-K)\)

D - hydraulic diameter, \(D = 4A_c/P_w\) \((m)\)

\(D_{coil}\) - coil external diameter \((m)\)

f - Moody friction factor

g - gravitational acceleration, \(g = 9.8 \text{ m/s}^2\)

G - mass flux, \(G = \rho_c v\) \((kg/m^2-s)\)

h - surface heat transfer coefficient \((W/m^2-K)\)

\(h_c\) - coolant enthalpy \((J/kg)\)

j - current density \((A/m^2)\)

k - thermal conductivity \((W/m-K)\)

\(K_c\) - coolant compressibility \((1/Pa)\)

L - length \((m)\)

\(L_m\) - radial thermal conduction path length in conductor \((m)\)

\(N_u\) - Nusselt number, \(N_u = hD/k_c\)

p - coolant pressure \((Pa)\)

Pr - Prandtl number, \(Pr = \mu_c c_p/k_c\)

\(P_h\) - heated perimeter \((m)\)

\(P_w\) - wetted perimeter \((m)\)

\(P_{elec}\) - electrical power \((W)\)

\(P_{heat}\) - external heat input power \((W)\)

\(P_{pump}\) - pump power \((W)\)

\(P_{refr}\) - refrigerator power \((W)\)

r - radial coordinate \((m)\)

\(Re\) - Reynolds number, \(Re = \rho_c vD/\mu_c\)

\(RRR\) - residual resistance ratio, \(RRR = \eta_{273K}/\eta_{0K}\)
List of Variables continued

\( t \) – time (s)
\( T \) – temperature (K)
\( T_r \) – reference temperature for refrigeration cycle (300 K)
\( T_c \) – mean coolant temperature (K)
\( v \) – coolant velocity (m/s)
\( V_m \) – conductor volume (m\(^3\))
\( x \) – axial coordinate (m)
\( \beta_c \) – coolant thermal expansivity (1/K)
\( \Delta t \) – time step size (s)
\( \Delta T_{\text{max}} \) – maximum magnet temperature rise (K)
\( \Delta T \) – average magnet temperature rise (K)
\( \Delta x \) – axial node length (m)
\( \epsilon_{\text{pump}} \) – pump hydraulic efficiency
\( \epsilon_{\text{refr}} \) – refrigerator non-Carnot efficiency
\( \eta \) – electrical resistivity (\( \Omega \cdot \text{m} \))
\( \theta \) – conductor angle from vertical
\( \tau_s \) – wall or surface shear stress (N/m\(^2\))
\( \rho \) – density (kg/m\(^3\))
\( \psi_c \) – coolant Joule-Thompson coefficient (m\(^2\)-K/J)

subscripts/superscripts

\( c \) – coolant
\( j \) – adjacent axial node
\( m \) – magnet or, more generally, conductor
\( n \) – axial node
\( s \) – surface
\( t \) – current time step
\( t - \Delta t \) – previous time step
\( tr \) – transverse heat conduction
This report describes the computer programs CCAN (steady-state Compressible Conductor Analysis) and TCAN (Time-dependent incompressible flow Conductor Analysis). These codes calculate temperature, pressure, power and other engineering quantities along the length of an actively cooled electrical conductor. They were developed to perform engineering analyses of internally-cooled conductors for non-superconducting magnets. Present versions contain detailed property information for copper and aluminum conductors; and gaseous helium, liquid nitrogen and water coolants.

The primary assumptions are:

1) Single phase flow;
2) Axial thermal conduction is small relative to heat transferred to coolant;
3) Conductor surfaces not in contact with coolant are adiabatic.

Section 1 reviews the general theory; Sections 2 and 3 describe the analysis used in CCAN and TCAN, respectively; Section 4 the present data base; Section 5 summarizes some validation runs; and Section 6 describes the input (similar for both programs).

1.0 General Theory

This analysis is restricted to single-phase, one-dimensional, constant area flow. It does include time-dependent heat sources, axial property variations, and compressible flow. The latter is required in general because of the large property variations possible at cryogenic temperatures with modest temperature changes (especially for gaseous coolants). The resulting equations do not lend themselves to analytic solution, but under the above assumptions with the additional neglect of azimuthal property variation, a simple marching procedure is adequate with straightforward differencing at each axial zone into coolant, conductor surface and conductor bulk nodes. Care must be taken to avoid choked flow and possible flow instabilities, critical heat flux with liquid coolants, and potential thermal runaway where resistivity changes rapidly with temperature.
In addition to the above assumptions, we neglect axial thermal conduction with respect to radial thermal conduction and consider only an average axial velocity, \( v \). Then, for the coolant, conservation of mass becomes [1]

\[
\frac{\partial \rho_c}{\partial t} + \frac{\partial}{\partial x}(\rho_c v) = \frac{\partial G}{\partial t} = 0
\]  

(1)

where \( G = \rho_c v \) is the mass flux, \( \rho_c \) the coolant density. The momentum equation with conservation of mass is [1]

\[
\frac{\partial G}{\partial t} + \frac{\partial}{\partial x}\left(\frac{G^2}{\rho_c}\right) + \frac{\partial p}{\partial x} + \frac{\tau_s P_w}{A_c} + \rho_c g \cos \theta = 0
\]  

(2)

where \( p \) is pressure, \( \tau_s \) is shear stress at the surface, \( x \) is the axial coordinate, \( P_w \) is the wetted perimeter, \( A_c \) is the coolant cross-sectional area, \( g \) gravitational acceleration and \( \theta \) is the conductor orientation angle clockwise from vertical. Expressing the wall shear in terms of a conventional friction factor \( f \) and the hydraulic diameter \( D \), and rearranging,

\[
\frac{\partial G}{\partial t} + \frac{\partial p}{\partial x} = -f \frac{G^2}{D} \frac{2\rho_c}{\rho_c} - \rho_c g \cos \theta - \frac{1}{\rho_c} \frac{\partial}{\partial x}\left(\frac{G^2}{\rho_c}\right)
\]  

(3)

The coolant energy equation with no internal heat sources is, [1]

\[
\left(\rho_c \frac{\partial}{\partial t} + G \frac{\partial}{\partial x}\right)(h_c + \frac{G^2}{2\rho_c}) - \frac{q'' P_h}{A_c} + G g \cos \theta - \frac{\partial p}{\partial t} = 0
\]  

(4)

where \( h_c \) is coolant enthalpy, \( q'' \) is the heat flux from conductor to coolant, and \( P_h \) is the heated perimeter.

The conductor equations are obtained from the cylindrical heat conduction equation, neglecting axial conduction and radial variation in thermal conductivity,

\[
\frac{1}{r} \frac{\partial}{\partial r}\left( r \frac{\partial T_m}{\partial r} \right) + \frac{q'''}{k_m} = \frac{1}{\rho_m c_m k_m} \frac{\partial T_m}{\partial t}
\]  

(5)

where \( r \) is radius, \( T_m \) is magnet temperature, \( q''' \) is volumetric heat source, \( \rho_m \) is magnet density, \( c_m \) is magnet specific heat and \( k_m \) is thermal conductivity.

Finally, the constitutive relations and empirical correlations [2] are

\[
q''' = \eta_m J^2 + q'''_{ext}
\]  

(6)

\[
q'' = h(T_{m, surface} - T_c) = q'' A_m \frac{P_h}{P_h}
\]  

(7)
\[ Nu = \frac{hD}{k_c} = 0.023Pr^{0.4}Re^{0.8} \left[ 1 + 3.5 \frac{D}{D_{coil}} \right] \]  

(8)

\[ f = \frac{0.316}{Re^{0.25}} \left( \frac{Re D^2}{D_{coil}^2} \right)^{0.05} \]  

(9)

In the above relations, \( \eta_m \) is the conductor electrical resistivity (evaluated at \( T_m \)); \( j \) is the current density in the conductor; \( q''''_{ext} \) is any external volumetric heat source; \( h \) is the heat transfer coefficient; \( Re, Nu \) and \( Pr \) are the usual Reynolds number (evaluated at film conditions in the \( Nu \) correlation), Nusselt number and Prandtl number, respectively, and the \( D/D_{coil} \) term is a curved pipe correction where \( D_{coil} \) is the mean coil external diameter or, equivalently, twice the coil radius of curvature.

The codes also calculate total electrical power \( P_{elec} \), mechanical pump power \( P_{pump} \), external heat input \( P_{heat} \) and refrigerator power \( P_{refr} \), in addition to the basic temperature and flow information,

\[ P_{elec} = \int_0^L \eta_m j^2 A_n dz \]  

(10)

\[ P_{pump} = \frac{1}{\epsilon_{pump}} \int_0^L \frac{G A_c}{\rho_c} dp \]  

(11)

\[ P_{heat} = \int_0^L q''''_{ext} A_n dz \]  

(12)

\[ P_{refr} = \frac{P_{pump} + P_{elec} + P_{heat}}{\epsilon_{refr}} \left( \frac{T_r}{T_c} - 1 \right) \]  

(13)

A pump hydraulic efficiency factor \( \epsilon_{pump} \) is included in the mechanical power expression, Eqn.(11), to allow for incomplete conversion of input electrical power to hydraulic pressure head. The remainder is wasted as heat and can be a significant heat source at cryogenic conditions. A reasonable value for room-temperature mechanical pumps is 70% [7]. Also, the design goal for the ISABELLE LHe (liquid helium) cold compressors is 70% isentropic efficiency [4].

Refrigeration power is estimated from a simple Carnot-type formula, Eqn.(13), where \( P_{pump} + P_{elec} + P_{heat} \) is the total thermal power to be removed; \( (T_r/T_c - 1) \) is the Carnot
"ideal refrigerator" factor, $T_r$ is the reference heat sink condition (say, atmosphere at 300 K); $\overline{T}_r$ is an average refrigeration temperature; and $\epsilon_{refr}$ is the actual non-Carnot refrigerator efficiency. Typical data on refrigerator efficiencies show more of a relationship of $\epsilon_{refr}$ with capacity than with temperature, and $\epsilon_{refr} \approx 0.2 - 0.30$ is typical for kW-to MW-rated units [5,6]. Since the refrigerator removes heat from the coolant over a temperature range $T_{c,max}$ to $T_{c,min}$ in the refrigerator, an average value $\overline{T}_c$ is used in the Carnot efficiency factor, where

$$\frac{1}{\overline{T}_c} = \frac{1}{T_{c,max} - T_{c,min}} \int_{T_{c,min}}^{T_{c,max}} \frac{dT}{T} = \frac{\ln(T_{c,max}/T_{c,min})}{T_{c,max} - T_{c,min}}$$

(14)

2.0 CCAN – Compressible-Flow Conductor Analysis

CCAN is limited, in addition to the approximations given in Section 1, to steady-state but compressible flow. Taking $\partial/\partial t = 0$ in Eqns. (1) to (5), we obtain

$$\frac{dG}{dx} = 0$$

(15)

$$\frac{dp}{dx} = -\frac{f G^2}{D 2\rho_c} - \rho_c g \cos \theta + \frac{G^2 d\rho_c}{\rho_c^2 dx}$$

(16)

$$G \frac{d h_c}{dx} - \frac{G^3 \rho_c}{\rho_c^3 dx} - \frac{q'' P_h}{A_c} + G g \cos \theta = 0$$

(17)

$$\frac{1}{r} \frac{d}{dr} \left( r \frac{dT_m}{dr} \right) = -\frac{q'''}{k_m}$$

(18)

We wish to determine $p(x)$, $T_c(x)$ and $T_m(x)$. Other variables such as $\rho_c$ and $h_c$ are in general functions of $p$ and $T_c$. So

$$\frac{d \rho_c}{dx} = \frac{\partial \rho_c}{\partial p} \left| \frac{dp}{dx} \right| + \frac{\partial \rho_c}{\partial T_c} \left| \frac{dT_c}{dx} \right|$$

(19)

and similarly for $(dh_c/dx)$. Making these expansions, substituting into the momentum and energy equations, and making use of the definitions of coolant compressibility $K_c$, thermal
expansivity \( \beta_c \), specific heat at constant pressure \( c_c \), and Joule-Thompson coefficient \( \psi_c \):

\[
K_c = \frac{1}{\rho_c} \left. \frac{\partial \rho_c}{\partial p} \right|_T
\]  
(20)

\[
\beta_c = -\frac{1}{\rho_c} \left. \frac{\partial \rho_c}{\partial T_c} \right|_p
\]  
(21)

\[
c_c = \frac{\partial h_c}{\partial T_c} \left|_p\right.
\]  
(22)

\[
\psi_c = -\frac{1}{c_c} \left. \frac{\partial h_c}{\partial p} \right|_T = \left. \frac{\partial T_c}{\partial p} \right|_h = -\frac{1}{\rho_c c_c} (1 - T_c \beta_c)
\]  
(23)

we finally obtain, where all quantities refer to fluid properties,

\[
\frac{dT_c}{dx} = \frac{1}{C} \left[ \frac{4q''}{GD c_c} + \frac{K_c G^2}{\rho_c c_c} \left( \frac{4q''}{GD} + \frac{f G^2}{D^2 \rho_c^2} \right) - \psi_c \rho_c \left( \frac{f G^2}{D^2 \rho_c^2} + \frac{g \cos \theta}{c_c} \right) \right]
\]  
(24)

\[
\frac{dp}{dx} = \frac{1}{C} \left[ -\beta_c G^2 \frac{4q''}{GD} + \frac{f G^2}{D^2 \rho_c^2} \right] - \rho_c \left( \frac{f G^2}{D^2 \rho_c^2} + \frac{g \cos \theta}{c_c} \right)
\]  
(25)

where

\[
C = 1 + \frac{\beta_c G^2}{\rho_c c_c} \left[ \frac{1}{\rho_c} + \psi_c c_c - \frac{K_c c_c}{\beta_c} \right]
\]  
(26)

Note that choked flow occurs when \( C \) goes to zero. Using the constitutive relations and property data, we can solve for \( p(x) \), \( T_c(x) \) and all the desired coolant quantities.

Applying an adiabatic outer boundary condition, we obtain, for an internal coolant channel,

\[
\Delta T_{\text{max}} = \frac{q^{''''}}{4\pi k_m} \left[ (A_m + A_c) \ln \left( \frac{A_c + A_m}{A_c} \right) - A_m \right]
\]  
(27a)

\[
\overline{\Delta T} = \frac{q^{''''}}{8\pi k_m} \left[ \frac{2(A_m + A_c)^2}{A_m} \ln \left( \frac{A_m + A_c}{A_c} \right) - 3A_m - 2A_c \right]
\]  
(27b)

and for an external coolant annulus (i.e., coolant in a ring outside a central solid conductor),

\[
\Delta T_{\text{max}} = \frac{q^{''''} A_m}{4\pi k_m}
\]  
(28a)
\[ \Delta T = \frac{q'''}{8\pi k_m} A_m \] (28b)

where \( \Delta T_{max} \) is the magnet temperature rise from the inner cooled surface to the outer surface, \( \Delta T \) is the average magnet temperature rise, and the result has been expressed in terms of coolant cross-sectional area \( A_c \) and magnet area \( A_m \).

3.0 TCAN – Time-Dependent Conductor Analysis

TCAN calculates time-varying temperature, pressure, power and other quantities along an axially cooled conductor, allowing variable current and inlet temperature, with an incompressible single-phase coolant. It is a modified version of TACC [3]. As in CCAN, the conductor is divided into axial zones, and each zone contains three lumped nodes representing bulk coolant, conductor/coolant interface and bulk conductor. Because of the explicit time and axial dependencies in the resulting equations, the heat transfer and pressure drop equations are written as finite difference equations and solved, for each time step, by marching from inlet to exit.

The general formulae are as in Section 1. We retain time-dependence but assume incompressible flow (\( \rho_c = \text{constant} \)). We also assume a pump-related boundary condition - constant inlet mass flow rate or \( \left( \frac{\partial G}{\partial t} \right)_{\text{inlet}} = 0 \). But then \( \frac{\partial G}{\partial x} = 0 \) since \( \rho_c \) is constant, so \( G \) is also fixed. The resulting equations are:

\[ G(x, t) = G_0 \] (29)

\[ \frac{\partial p}{\partial x} + \frac{f G^2}{2 \rho_c} + \rho_c g \cos \theta = 0 \] (30)

\[ \rho_c \frac{\partial h_c}{\partial t} + G \frac{\partial h_c}{\partial x} - \frac{q'''}{A_c} + G g \cos \theta = 0 \] (31)

\[ \frac{k_m}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T_m}{\partial r} \right) + q''' = \frac{1}{\rho_m c_m} \frac{\partial T_m}{\partial t} \] (32)

In the actual implementation of these equations, properties are evaluated at the most recent time or axial node conditions, and \( \rho_c \) in particular may change. Consequently, the incompressibility assumption is relaxed somewhat and replaced by the assumption
that the compressibility terms in the fluid equations can be neglected with respect to the other terms. Furthermore, the compressibility-related term \((\partial \rho_c / \partial x) G^2 / \rho_c^2\) in the pressure equation is retained to improve prediction of choked flow conditions.

As in the CCAN analysis, \(\rho_c = \rho_c(p, T)\) and \(h_c = h_c(p, T)\). In general, \(dh_c = -c_c \psi_c dp + c_c dT_c\) where \(\psi_c\) is the Joule-Thompson coefficient. We neglect \(\psi_c\) in TCAN since situations where the Joule-Thompson effect matters usually require full compressible flow analysis anyway (e.g. gaseous helium below 10 K), so \(dh_c = c_c dT_c\) and the energy equation simplifies to

\[
\rho_c \frac{\partial T_c}{\partial t} + G_c \frac{\partial T_c}{\partial x} = q'' P_h / \rho_c + G_c \cos \theta = 0
\] (33)

Eqns. (30), (32) and (33) are written in a partially implicit finite difference form as:

**Coolant momentum equation (node \(n + 1\) at time step \(t\)):**

\[
\frac{p_{c,n+1}^t - p_{c,n}^t}{\Delta x} + f_{c,n+1}^t - f_{c,n}^t + \frac{\rho_c G^2}{2 \rho_c} + \frac{\Delta \rho_c G^2}{\Delta x \rho_c^2} \Delta t = 0 \] (34)

**Coolant energy equation (node \(n + 1\) at time \(t\)):**

\[
\rho_c c_c \left( \frac{T_{c,n+1}^t - T_{c,n+1}^t}{\Delta t} \right) + G_c \frac{T_{c,n+1}^t + T_{c,n+1}^t}{2} - \frac{T_{c,n}^t + T_{c,n}^t}{2} = 0 \] (35)

**Conductor bulk energy equation (node \(n\) at time step \(t\)):**

\[
- \frac{P_h \Delta x k_m}{L_m} (T_{m,n}^t - T_{s,n}^t) - h_{tr} A_{tr} (T_{m,n}^t - T_{m,n}^t) + A_m \Delta x \left( \frac{q^t + q^{t-\Delta t}}{2} \right) = A_m \Delta x \left( \frac{T_{m,n}^t - T_{m,n}^t}{\Delta t} \right) \] (36)

**Interface temperature equation (node \(n\) at time \(t\)):**

\[
\frac{k_m}{L_m} (T_{m,n}^t - T_{s,n}^t) = h (T_{s,n}^t - T_{c,n+1}^t) \] (37)

where the superscript denotes the time step; subscripts \(c, m\) and \(s\) indicate coolant, magnet (conductor) and surface (interface) values; subscripts \(n, n+1\) and \(j\) denote axial
node; \( q \) is an external volumetric heat source; \( L_m \) is an effective thermal conduction path length between the conductor bulk temperature node and the interface temperature node; and \( h_i, A_i \) is an effective heat transfer coefficient and area for heat transfer between axial nodes \( n \) and \( j \).

In these difference equations, coolant node 1 is the inlet, so coolant node 2 is the first axial node actually in the conductor and corresponds to conductor node 1. The variables are referred to time steps \( t \) or \( t - \Delta t \) so as to make the most important variables implicit and other terms estimated explicitly from previous time step values. As a result of this differencing, the equations can be solved directly for \( T_{c,n+1}^t, T_{s,n}^t, T_{m,n}^t \) and \( p_{n+1}^t \) in terms of known previous time step and axial node values, yielding:

\[
T_{c,n+1}^t = C_1 C_2 \left( \frac{k_m P_h A_m \Delta x \Delta t}{L_m (1 + k_r)} \right) \left[ A_m \Delta x \Delta t q + A_m \Delta x \rho_m c_m T_{m,n}^{t-\Delta t} - h_i A_i \Delta t (T_{m,n}^{t-\Delta t} - T_{m,j}^{t-\Delta t}) \right] + C_1 \left[ \frac{G A_c c_c \Delta t}{2} \left( T_{c,n}^t + T_{c,n}^{t-\Delta t} - T_{c,n+1}^{t-\Delta t} \right) + A_m \Delta x \rho_m c_m - A_c \Delta x \Delta t G g \cos \theta \right] \tag{38}
\]

\[
T_{m,n}^t = C_2 \left[ A_m \Delta x \Delta t q + A_m \Delta x \rho_m c_m T_{m,n}^{t-\Delta t} \right.
+ \left. \frac{k_m P_h A_m \Delta x \Delta t}{L_m (1 + k_r)} T_{c,n+1}^t - h_i A_i \Delta t (T_{m,n}^{t-\Delta t} - T_{m,j}^{t-\Delta t}) \right] \tag{39}
\]

\[
T_{s,n}^t = \frac{T_{c,n+1}^t + k_r T_{m,n}^t}{1 + k_r} \tag{40}
\]

\[
p_{n+1}^t = p_n^t - \frac{f^{t-\Delta t}}{D} \frac{G^2}{2 \rho_c} - \rho_g \cos \theta + \left[ \frac{\Delta \rho_c G^2}{\Delta x \rho_c^2} \right]^{t-\Delta t} \tag{41}
\]

where \( k_r = k_m / h L_m \); \( L_m \approx (\sqrt{A_m + A_c} - \sqrt{A_c}) / 2 \sqrt{\pi} \) is the approximate radial conduction length with internal cooling, and \( L_m \approx \sqrt{A_m / \pi} / 2 \) is the average radial length for solid conductors with external cooling; \( q = (q^t - q^{t-\Delta t}) / 2 \); and

\[
\frac{1}{C_1} = A_c \Delta x \rho_c c_c + \frac{G A_c c_c \Delta t}{2} + \frac{k_m P_h A_m \Delta x \rho_m c_m}{L_m (1 + k_r) A_m \Delta x \rho_m c_m + k_m P_h A_m \Delta x \Delta t} \tag{42a}
\]

\[
\frac{1}{C_2} = A_m \Delta x \rho_m c_m + \frac{k_m P_h A_m \Delta t}{L_m (1 + k_r)} \tag{42b}
\]
4.0 Materials Properties and Other Data

CCAN and TCAN contain extensive libraries of materials properties. These are generally stored in two-dimensional arrays and values obtained by linear-linear interpolation.

4.1 Conductor Properties

The present data base is for copper and aluminum conductors. The data consists of the basic zero field properties stored in a 2-D array form for a wide range of temperature and purities, plus correlations for the effect of magnetic fields.

For copper, the thermal conductivity, specific heat and electrical resistivity are accurate over 4 - 600 K and 30 - 3000 RRR, where RRR is Residual Resistance Ratio, $\eta_{273K}/\eta_{0K}$, is a measure of purity [8]. A single median value for density is used throughout this range. Magnetic field effects on electrical resistivity are included using the Kohler equation form

$$
\ln \left( \frac{\eta(B, T) - \eta(0, T)}{\eta(0, T)} \right) = -7.00 + 1.383 \left[ \ln \frac{B \eta(0, 273K)}{\eta(0, T)} \right] - 0.0298 \left[ \ln \frac{B \eta(0, 273K)}{\eta(0, T)} \right]^2
$$

This is a good fit to copper data over 0 to 10 Tesla.

For aluminum, the thermal conductivity, specific heat and electrical resistivity are accurate over 4 - 600 K and 30 - 3000 RRR [8]. A single median value for density is used throughout this range. Magnetic field effects on electrical resistivity are included using the Kohler equation form

$$
\eta(B, T) = \eta(0, T) \left[ 1 + 0.00177 \frac{B \eta(0, 273K)/\eta(0, T)}{1 + 0.0005 B \eta(0, 273K)/\eta(0, T)} \right]
$$

This is only an approximate fit to aluminum data over 0 to 10 Tesla, which seemed fairly scattered [9,10,11].

There is limited data available on magnetoconductivity, but enough to indicate substantial reductions in thermal conductivity in high purity, low temperature copper and aluminum as magnetic field increases to 8 T or so [8,12]. In order to estimate this effect, note that for pure metals in no magnetic field, $k_m \eta_m \simeq CT$, where $C = 2.45 \times 10^{-8}$ W$\cdot$K$^{-2}$. Since $k_m$ and $\eta_m$ depend on conduction electrons (not phonons), we assume that magnetic fields decrease thermal and electrical conductivity proportionally. This overestimates the reduction of $k_m$, especially in strong fields, since phonon heat conduction provides a lower limit to thermal conductivity. The final scaling equation used is

$$
\frac{k_m(B, T)}{k_m(0, T)} = 0.2 + 0.8 \frac{\eta_m(0, T)}{\eta_m(B, T)}
$$

9
The magnetic field effect on resistivity is obtained from Eqns.(43) and (44). For alloys, thermal conduction depends strongly on phonons so magnetoconductivity effects are small.

4.2 Coolant Properties

Gaseous helium, liquid nitrogen and liquid water properties are included as functions of temperature and pressure [16]. Magnetic field effects are assumed negligible.

For all coolants, the needed properties are specific heat, viscosity, thermal conductivity and density. The data ranges are 6 - 600 K and 0.1 to 15 MPa for \( g\text{He} \); 65 - 125 K and 0.1 - 15 MPa for \( l\text{N}_2 \); and 273 - 613 K, 0.1 - 15 MPa for \( l\text{H}_2\text{O} \). Note that the \( \text{N}_2 \) data includes the critical point (126.2 K, 3.396 MPa) and data (especially specific heat) should be considered only approximate near these conditions. Saturation pressure correlations are needed for \( l\text{N}_2 \) and \( l\text{H}_2\text{O} \) to determine the onset of boiling, and are expressed as

\[
p_{sat}(l\text{N}_2) = 9.473 \times 10^8 \exp(-707.4/T) \quad (46a)
\]

\[
p_{sat}(l\text{H}_2\text{O}) = 5.157 \times 10^5(T - 255.2)^{-1.484} \quad (46b)
\]

Both viscosity and saturation pressures are evaluated at film temperature - half-way between the coolant bulk temperature and the wall surface temperature.

For all coolants, the compressibility \( K_c \) and expansivity \( \beta_c \) are defined in Eqns.(20) and (21), and are obtained by estimating the derivatives of \( \rho_c \) from the \( \rho_c(P, T_c) \) data. The Joule-Thompson coefficient \( \psi_c \) represents an interesting property and is treated somewhat differently. In general, it is the isenthalpic change of temperature with pressure and is negative, indicating heating with pressure drop. However for helium gas (and others such as \( \text{H}_2 \) and \( \text{Ne} \)), the potential energy of intermolecular attraction can increase as pressure drops, resulting in a drop in gas temperature. For helium, this occurs in a range of \((T, P)\) roughly bounded by \((40 \text{ K}, 0 \text{ MPa})\), \((20 \text{ K}, 2 \text{ MPa})\) and \((0 \text{ K}, 0 \text{ MPa})\). This effect may be useful in cryogenic \( g\text{He} \)-cooled systems where a sufficient pressure drop per unit length may supply enough \(-\Delta T\) from the Joule-Thompson effect to counter the \(+\Delta T\) picked up the the helium coolant, resulting in a very uniform temperature along the cooled length. This effect is not important for \( l\text{N}_2 \) or \( l\text{H}_2\text{O} \), so \( \psi_c \) is only crudely estimated from \( \beta_c \) as given by Eqn.(23). However, since it may be a significant or desired contribution in cryogenic \( g\text{He} \) systems, enthalpy values for helium from 6 - 600 K and 0.1 - 15 MPa are
supplied and \( \psi_c \) estimated as \( \psi_c = -\left( \frac{\partial e_c}{\partial p} \right)_T / \alpha_c \). If more accuracy is needed, values of \( \psi_c \) should be provided directly.

5.0 Sample Runs and Validation

5.1 Water-cooled copper conductors – steady-state

Anaconda Copper published a technical report [13] that describes their hollow copper conductors and provides engineering diagrams relating current, coolant velocity, coolant temperature rise and coolant pressure drop. Three cases were selected and analyzed using both CCAN and TCAN (run until steady-state reached). The results are in Table 2. The calculated values were obtained by interpolating on the Anaconda report charts as well as from standard correlations.

5.2 Transient cooldown

According to heat conduction theory, if a body is suddenly immersed in a coolant at a temperature \( T_{ci} \), with surface heat transfer coefficient \( h \) and negligible internal temperature gradients (\( k_m A_m / h V_m > 6 \)), then [2],

\[
\frac{q'''' V_m / h A_m - T_m + T_{ci}}{q'''' V_m / h A_m - T_{m0} + T_{ci}} = \exp \left[ \frac{-A_m h t}{V_m \rho_m c_m} \right] \tag{47}
\]

where \( q'''' \) is internal heat rate; \( V_m / A_m = A_m / P_h \) is the volume-to-surface-area ratio for axially cooled conductors; and \( T_{m0} \) is initial conductor temperature.

Figure 1 compares this theory with TCAN calculations for a thin internally-cooled copper conductor in \( \ell N_2 \) (\( k_m A_m / h V_m \approx 100 \)). The differences become larger with time because property values change slightly in TCAN while only constant initial values were used in the theoretical curve.

5.3 Long cryogenic gHe cooled tubes

In an experimental simulation of a superconducting power transmission line cooled by 10 K gHe, a long (\( L/D \approx 10^5 \)) copper cable was studied to determine steady-state performance [14]. The three cases reported provide a good test of the compressible flow features, including the Joule-Thompson effect. The overall parameters are 0.181 \( \text{cm}^2 \) flow area, 300-500 m long tubes wrapped in a large drum with 22 m/turn, and heat leaks of 0.06 to 0.09 W/m. Figure 2 shows the experimental and calculated results.
Case 1 was a straightforward, relatively incompressible case, and agreed reasonably with CCAN and TCAN. Cases 2 and 3 involved compressible flow where CCAN is more appropriate. Here, CCAN matched the experimental results well, but required 10-20% higher mass flows than measured (which were somewhat uncertain themselves).

5.4 Instabilities with cryogenic gHe

Cryogenic gas cooled electric current leads are used to supply power to superconducting magnets. A flow instability related to rapid variation of properties with temperature, particularly viscosity, can result in loss of cooling. Here, experimental and theoretical predictions [15] are compared with CCAN results. The "hot" and "cold" leads are modelled separately as internally-cooled, horizontal copper conductors at about 6 K and 0.1 MPa. The cold lead was 0.66 m long, with $A_m = 0.135$ cm$^2$; $A_c = 0.20$ cm$^2$; $P_h = 1.3$ cm, $P_v = 3.352$ cm; and 0.326 W/lead heat leak. The "hot" lead had wider flow passages so was less susceptible to the flow instability.

Figure 3 shows the reported results and CCAN predictions. Onset of the instability was indicated by lack of convergence and/or rapidly escalating temperatures. Two differences between CCAN and the reported results were the 6 K used in CCAN versus the 4 K in the experiments (CCAN property correlations only go down to 6 K), and the neglect of axial thermal conduction in CCAN. These do not seem to be critical since agreement is good. Four runs with TCAN also agreed with the stability boundary as shown, although an exact threshold is difficult to pin down with TCAN because computer time gets large as the boundary is approached.

6.0 Input/Output

The input variables for CCAN and TCAN are almost identical, and are described in Table 1 with code specific differences marked. Namelist input format is used, so input data can be free-formatted in random order. Sample inputs are shown in Appendix A. Note that the programs are currently inclined towards, but not exclusive for, spiral wound pancake-type magnets.

The output file contains: an input data listing; initial inlet property data; numerical results at different space and time points; final exit property data; and computational time. In CCAN, coolant, interface and maximum conductor temperature data, pressure and
Reynolds number profiles are provided at axial points. In TCAN, similar axial temperature data, exit pressure, exit Reynolds number and power consumption are given at time points. In addition, TCAN can plot conductor temperature at the inlet, middle and exit. The plot time points are the same as the print time points. Note that the plot arrays are of limited size – about 300 time points are currently stored.

A description of how to compile, load and execute is provided at the start of each program's source listing. CCAN and TCAN are currently available on the NMFECC CDC 7600 machine, using CHATR to compile (ignore the warning messages), DISSLIB and TV80LIB for plotting, FORTLIB for file linking and utilities, INCAN for the input files, and OCAN and OTAN for output files.

Both CCAN and TCAN have internal error control and convergence parameters that are preset to reasonable values in DATA statements at the start of the main program. CCAN limits the number of iterations \((N_{\text{MAX}} = 30)\) at each axial step, unless satisfactory convergence \((EPS = 0.001\ %)\) is achieved on magnet temperature. TCAN chooses a time step based on a fraction \((ADT = 0.1)\) of the smaller of: 1) the time between points in the input current/internal heating/coolant temperature data; 2) the time for the coolant to traverse an axial node; and 3) the conductor heat transfer time constant \((A_m \rho_m c_m / P_{th})\).

7.0 Conclusions

CCAN and TCAN are reasonably fast, versatile codes for the thermal-hydraulic analysis of many non-superconducting actively-cooled conductors. These programs have been used to analyze ISX-B, TEXTOR and ALCATOR-C bundle divertor designs, TARA mirror coils, and FED copper magnet inserts. Both CCAN and TCAN are available from the authors on the NMFECC CDC 7600 computer.
8.0 References


APPENDIX A: SAMPLE RUNS

Sample inputs and outputs from validation runs described in Section 5 are listed here to indicate format. The CCAN sample is Case 2 of Section 5.3, a long cryogenic \textit{gHe} cooled tube. This case required 0.26 s of computer time. The TCAN sample is from Case 1 of Section 5.1, a water-cooled copper conductor starting at room temperature. This case required 97 s of computer time to analyze 150 s of real time.

Sample CCAN Input

\begin{verbatim}
iname="heli" "um c" "oole" "d tr" "ansm" "issi" "on l" "ine" "test"
nodes=300 nturns=23 im=1 ic=1 iprn=20 ncoils=1
axm=0.50e-4 axc=0.181e-4 pw=0. ph=0. length=21.92 costh=0.
mrot=0.0033 bmag=0. rrr=100. pin=1.0e+6 effp=1. effr=0.25
tci=9.5
qint=1240.
amps=0. $
\end{verbatim}

Sample TCAN Input

\begin{verbatim}
iname=" ***" "ana" "cond" "a cu" "-h2o" " cod" "e te" "st a" "3 ***
nodes=31 nturns=1 im=1 ic=3 iprn=15 ncoils=1 mn=3 ncycle=1
axm=0.01 axc=0. ph=0. pw=0.1571 length=18.3 costh=1.0e-8
mdot=10. bmag=0. rrr=100. pin=0.30e7 effp=0.7 effr=0.25 tmi=280.
hist=0. 1. 150.
amps=0. 50000. 50000.
tci=280. 280. 280.
qint=0. 0. 0.
dtpr1=2.0 dtpr2=50. dtbrk=4. tpron=0. tpron=0.
he=0. width=0. rmax=0. $\end{verbatim}
ccan(1982) compressible flow analysis:

ccan(1982) compressible flow analysis:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass flow (kg/s)</td>
<td>0.00330</td>
</tr>
<tr>
<td>Mass flux/coil (kg/m²-s)</td>
<td>182.320</td>
</tr>
<tr>
<td>Inlet pressure (mpa)</td>
<td>1.00</td>
</tr>
<tr>
<td>Inlet temperature (k)</td>
<td>9.5</td>
</tr>
<tr>
<td>Current area (cm²)</td>
<td>0.50</td>
</tr>
<tr>
<td>Flow area (cm²)</td>
<td>0.18</td>
</tr>
<tr>
<td>Heated perimeter (cm)</td>
<td>1.508</td>
</tr>
<tr>
<td>Wetted perimeter (cm)</td>
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</tr>
<tr>
<td>Magnet current (ka)</td>
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</tr>
<tr>
<td>Magnet current density (ka/cm²)</td>
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</tr>
<tr>
<td>Length/turn (m)</td>
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<tr>
<td>Effective coil radius (m)</td>
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<tr>
<td>Number coils</td>
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<td>Cosine (angle from vertical)</td>
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<td>Current (1=cu, 2=al)</td>
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<td>Refrigerator efficiency (%)</td>
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<td>Internal heating (mw/m³)</td>
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<td>Field strength (tesla)</td>
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Coolant properties at 9.5 k, 1.00 mpa:

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<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>CP (J/kg·K)</td>
<td>7271.88</td>
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<tr>
<td>Rho (kg/m³)</td>
<td>70.15</td>
</tr>
<tr>
<td>Mu (kg/s)</td>
<td>0.024</td>
</tr>
<tr>
<td>Compressibility d(rho)/d(p)*1/rho (1/pa)</td>
<td>4.712e-07</td>
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<tr>
<td>Expansitivity -d(rho)/d(t)*1/rho (1/k)</td>
<td>2.462e-01</td>
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<tr>
<td>Joule-Thompson coefficient -d(h)/d(p)*1/cp (k/pa)</td>
<td>1.991e-07</td>
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<tr>
<td>Saturation pressure psat (mpa)</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Magnet properties at 9.5 k:

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Rho (kg/m³)</td>
<td>1.445e+03</td>
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<tr>
<td>Resistivity (ohm·m)</td>
<td>1.570e-10</td>
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<tr>
<td>Residual resistance ratio (res273/res0)</td>
<td>100.00</td>
</tr>
</tbody>
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<tr>
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<th>Tmag</th>
<th>Tmout</th>
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<td>9.58</td>
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<td>0.48</td>
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Magnet power requirements (mw):

<table>
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<th>Node</th>
<th>Total Coil Electrical Pumping Cooling Total Sources Exit P(mpa) T(k)</th>
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</thead>
<tbody>
<tr>
<td>0.0083</td>
<td>0.0000 0.0002 0.0083 0.0000 0.48 9.8</td>
</tr>
</tbody>
</table>
coolant properties at $9.8 \text{k}$; $0.48 \text{mpa}$

$\begin{align*}
\text{cp (j/kg-k)} &= 6719.43 \\
\text{rho (kg/m3)} &= 31.28 \\
\mu (kg/m-s) &= 0.259e-05 \\
\text{k (w/m-k)} &= 0.020 \\
\text{compressibility d(rho)/d(p)*1/rho (1/pa)} &= 2.506e-06 \\
\text{expansivity -d(rho)/d(t)*1/rho (1/k)} &= 3.779e-01 \\
\text{joule-thompson coefficient -d(h)/d(p)*1/cp (k/pa)} &= 2.968e-06 \\
\text{saturation pressure psat (mpa)} &= 0.
\end{align*}$

magnet properties at $9.8 \text{k}$

$k (w/m-k) = 1.483e+03$ $\text{resistivity (ohm-m)} = 1.570e-10$

$\begin{align*}
\text{residual resistance ratio (res273/res0)} &= 100. \\
\text{exit velocity (m/s)} &= 5.83 \\
\text{calculational time (s)} &= 0.2596
\end{align*}$

Sample TCAN Output

tcan(1962) time dependent flow analysis:

$\begin{align*}
\text{*** anaconda cu-h2o code test a3 ***} \\
\text{total mass flow (kg/s)} &= 10.00000 \\
\text{mass flux/coil (kg/m2-s)} &= 5091.637 \\
\text{inlet pressure (mpa)} &= 3.00 \\
\text{inlet temperature (k)} &= 288.0 \\
\text{current area (cm2)} &= 100.00 \\
\text{flow area (cm2)} &= 19.64 \\
\text{heated perimeter (cm)} &= 15.710 \\
\text{wetted perimeter (cm)} &= 15.710 \\
\text{length/turn (m)} &= 18.30 \\
\text{number turns} &= 1 \\
\text{effective coil radius (m)} &= * \\
\text{number of nodes} &= 31 \\
\text{cosine(angle from vertical)} &= 0.000 \\
\text{number of coils} &= 1 \\
\text{magnetic field} &= 0. \\
\text{pump hydraulic efficiency ()} &= 70. \\
\text{refrigerator efficiency ()} &= 25. \\
\text{conductor (1-cu,2=al)} &= 1 \\
\text{coolant (1=he,2=ln2,3=water)} &= 3 \\
\text{time controls (s): tend= 150.0 step= 0.0116} \\
\text{initial print step= 2.00 final print step= 50.00 print step change= 4.00} \\
\text{iprn= 15 mn= 3 nodes= 31 ncycle= 1 time plot on= 0.}
\end{align*}$

$\begin{align*}
\text{coolant properties at t(k)=280.0 p(mpa)} &= 3.00 \\
\text{kc(w/m-k)} &= 0.583 \\
\text{rho(cm3/kg)} &= 1001.2 \\
\text{cpc(j/kg-k)} &= 4.198e+03 \\
\text{muc(kg/m-s)} &= 1.489e-03
\end{align*}$

$\begin{align*}
\text{magnet properties at t(k)=280.0} \\
\text{km(w/m-k)} &= 396.9 \\
\text{rhom(kg/m3)} &= 8930. \\
\text{cpm(j/kg-k)} &= 376.0 \\
\text{resm(ohm-m)} &= 1.614e-08 \\
\text{res273(ohm-m)} &= 1.570e-08 \\
\text{rrr} &= 100.0
\end{align*}$

$\begin{align*}
\text{time(s)} & \quad \text{current(amps)} & \quad \text{inlet temp(k)} & \quad \text{int heat source(kw/m3)} \\
0. & \quad 0. & \quad 280.000 & \quad 0. \\
1.000 & \quad 50000.000 & \quad 280.000 & \quad 0. \\
150.000 & \quad 50000.000 & \quad 280.000 & \quad 0.
\end{align*}$
adjacent nodes for cross-node heat transfer

<p>| | | | | | | |</p>
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</table>

\[\text{time} = 0. \text{ sec}\]

\begin{align*}
\begin{array}{cccccccc}
 n & \text{tc} & \text{ts} & \text{tm} & n & \text{tc} & \text{ts} & \text{tm} \\
1 & 280.0 & 280.0 & 280.0 & 16 & 280.0 & 280.0 & 280.0 \\
31 & 280.0 & 280.0 & 280.0 & 31 & 280.0 & 280.0 & 280.0 \\
\end{array}
\end{align*}

\[\text{time} = 2.00 \text{ sec}\]

\begin{align*}
\begin{array}{cccccccc}
 n & \text{tc} & \text{ts} & \text{tm} & n & \text{tc} & \text{ts} & \text{tm} \\
1 & 280.0 & 280.1 & 280.2 & 16 & 280.0 & 280.1 & 280.2 \\
31 & 280.0 & 280.1 & 280.2 & 31 & 280.0 & 280.1 & 280.2 \\
\end{array}
\end{align*}

\begin{align*}
\text{exit re}=171345. & \quad \text{exit } h(\text{kw/m}^2\text{-k})=10.6 & \quad \text{current(ka)}=50.00 \\
\text{total energy added}(j)=9.8e+04 & \\
\text{total energy transferred to coolant }(j)=2.09e+03 & \\
\text{electric power (kw)}=73.9 & \quad \text{internal heating (kw)}=0. \\
\text{refrigeration power (kw)}=21.4 & \quad \text{pumping power (kw)}=1.1 \\
\text{exit p (mpa)}=2.92 & \\
\end{align*}

\[\text{time} = 3.99 \text{ sec}\]

\begin{align*}
\begin{array}{cccccccc}
 n & \text{tc} & \text{ts} & \text{tm} & n & \text{tc} & \text{ts} & \text{tm} \\
1 & 280.0 & 280.3 & 280.4 & 16 & 280.0 & 280.3 & 280.4 \\
31 & 280.0 & 280.1 & 280.3 & 31 & 280.0 & 280.1 & 280.3 \\
\end{array}
\end{align*}

\begin{align*}
\text{exit re}=171967. & \quad \text{exit } h(\text{kw/m}^2\text{-k})=10.7 & \quad \text{current(ka)}=50.00 \\
\text{total energy added}(j)=2.5e+05 & \\
\text{total energy transferred to coolant }(j)=1.18e+04 & \\
\text{electric power (kw)}=74.0 & \quad \text{internal heating (kw)}=0. \\
\text{refrigeration power (kw)}=21.4 & \quad \text{pumping power (kw)}=1.1 \\
\text{exit p (mpa)}=2.92 & \\
\end{align*}

\[\text{time} = 5.99 \text{ sec}\]

\begin{align*}
\begin{array}{cccccccc}
 n & \text{tc} & \text{ts} & \text{tm} & n & \text{tc} & \text{ts} & \text{tm} \\
1 & 280.0 & 280.4 & 280.5 & 16 & 280.1 & 280.4 & 280.5 \\
31 & 280.0 & 280.1 & 280.5 & 31 & 280.0 & 280.1 & 280.5 \\
\end{array}
\end{align*}

\begin{align*}
\text{exit re}=172518. & \quad \text{exit } h(\text{kw/m}^2\text{-k})=10.7 & \quad \text{current(ka)}=50.00 \\
\text{total energy added}(j)=3.9e+05 & \\
\text{total energy transferred to coolant }(j)=2.87e+04 & \\
\text{electric power (kw)}=74.0 & \quad \text{internal heating (kw)}=0. \\
\text{refrigeration power (kw)}=21.4 & \quad \text{pumping power (kw)}=1.1 \\
\text{exit p (mpa)}=2.92 & \\
\end{align*}

\[\text{time} = 55.99 \text{ sec}\]

\begin{align*}
\begin{array}{cccccccc}
 n & \text{tc} & \text{ts} & \text{tm} & n & \text{tc} & \text{ts} & \text{tm} \\
1 & 280.0 & 282.1 & 283.1 & 16 & 280.7 & 282.6 & 283.5 \\
31 & 280.1 & 283.0 & 283.9 & 31 & 280.1 & 283.0 & 283.9 \\
\end{array}
\end{align*}

\begin{align*}
\text{exit re}=182957. & \quad \text{exit } h(\text{kw/m}^2\text{-k})=11.0 & \quad \text{current(ka)}=50.00 \\
\text{total energy added}(j)=4.1e+06 & \\
\text{total energy transferred to coolant }(j)=1.97e+06 & \\
\text{electric power (kw)}=74.9 & \quad \text{internal heating (kw)}=0. \\
\text{refrigeration power (kw)}=20.9 & \quad \text{pumping power (kw)}=1.1 \\
\text{exit p (mpa)}=2.92 & \\
\end{align*}
time = 106.00 sec
   n  tc  ts  tm  n  tc  ts  tm  n  tc  ts  tm
1  280.1 282.4 283.6 16  280.9 283.1 284.3 31  281.7 283.8 284.9
exit re=186410.  exit h(kw/m**2-k)= 11.0  current(ka)= 50.00
total energy added(j)= 7.9e+06
total energy transferred to coolant (j)= 5.25e+06
electric power (kw)= 75.1 internal heating (kw)= 0.
refrigeration power (kw)= 20.8 pumping power (kw)= 1.1
exit p (mpa)= 2.92

time = 150.00 sec
   n  tc  ts  tm  n  tc  ts  tm  n  tc  ts  tm
1  280.1 282.4 283.6 16  280.9 283.1 284.4 31  281.8 284.1 285.2
exit re=187357.  exit h(kw/m**2-k)= 11.1  current(ka)= 50.00
total energy added(j)= 1.1e+07
total energy transferred to coolant (j)= 8.44e+06
electric power (kw)= 75.1 internal heating (kw)= 0.
refrigeration power (kw)= 20.8 pumping power (kw)= 1.1
exit p (mpa)= 2.92

coolant properties at t(k)=281.7 p(mpa)= 2.92
   kc(w/m-k)= 0.586  rhoc(kg/m**3)=1001.0
cpc(j/kg-k)= 4.197e+03  muc(kg/m-s)= 1.359e-03

magnet properties at t(k)=285.2
   km(w/m-k)= 396.8  rhom(kg/m**3)=8930.
cpm(j/kg-k)= 376.8  resm(ohm-m)= 1.647e-08
res273(ohm-m)= 1.570e-08  rrr= 100.0

calculational time (s) = 97.1140
Sample TCAN Plot

MASS FLOW (KG/S) = 1.0 x 10^1
AVG COIL RADIUS (M) = 1.0 x 10^N

COIL TEMPERATURE

T (S)
Table 1: Input Variables for CCAN and TCAN

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>INAME</td>
<td></td>
<td>80 character title for printout</td>
</tr>
<tr>
<td>NODES</td>
<td></td>
<td>Number of axial nodes (max 300)</td>
</tr>
<tr>
<td>NTURNS</td>
<td></td>
<td>Number of conductor turns (1 if single length)</td>
</tr>
<tr>
<td>IM</td>
<td></td>
<td>Conductor material: 1/2 = copper/aluminum</td>
</tr>
<tr>
<td>IC</td>
<td></td>
<td>Coolant material: 1/2/3 = ( gHe/\ell N_2/\ell H_2O )</td>
</tr>
<tr>
<td>IPRN</td>
<td></td>
<td>Temperature printout control: every IPRN’th axial node</td>
</tr>
<tr>
<td>NCOILS</td>
<td></td>
<td>Number of conductor coils</td>
</tr>
<tr>
<td>AXM</td>
<td>( \text{m}^2 )</td>
<td>Conductor cross-sectional area</td>
</tr>
<tr>
<td>AXC</td>
<td>( \text{m}^2 )</td>
<td>Coolant cross-sectional area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total magnet cross-sectional area is ( \text{AXM} + \text{AXC} ) plus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>support and insulation for each turn.</td>
</tr>
<tr>
<td>PH</td>
<td>( \text{m} )</td>
<td>Heated perimeter</td>
</tr>
<tr>
<td>PW</td>
<td>( \text{m} )</td>
<td>Wetted perimeter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If any of AXC, PH or PW are zero, the program assumes a circular channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with area AXC, or perimeter PW, or perimeter PH (in that order) and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>calculates the remaining dimensions.</td>
</tr>
<tr>
<td>LENGTH</td>
<td>( \text{m} )</td>
<td>Length of one conductor turn</td>
</tr>
<tr>
<td>COSTH</td>
<td></td>
<td>Cosine of angle from vertical; for example, ( \text{COSTH} = -1 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>indicates vertical flow downwards; ( \text{COSTH} = 0 ) is a special</td>
</tr>
<tr>
<td></td>
<td></td>
<td>case and indicates a spiral wound coil with no net height change, ( \text{COSTH} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>arbitrarily small but non-zero indicates straight and horizontal coil.</td>
</tr>
<tr>
<td>MDOT</td>
<td>( \text{kg/s} )</td>
<td>Mass flow rate per coil</td>
</tr>
<tr>
<td>BMAG</td>
<td>Tesla</td>
<td>Magnetic field in conductor</td>
</tr>
<tr>
<td>RRR</td>
<td></td>
<td>Residual Resistance Ratio ( \eta_{0K}/\eta_{273K} )</td>
</tr>
<tr>
<td>PIN</td>
<td>( \text{Pa} )</td>
<td>Inlet pressure</td>
</tr>
<tr>
<td>EFFP</td>
<td></td>
<td>Fractional pump hydraulic efficiency</td>
</tr>
<tr>
<td>EFFR</td>
<td></td>
<td>Fractional refrigerator non-Carnot efficiency</td>
</tr>
</tbody>
</table>

22
Table 1 (continued): Input Format for CCAN and TCAN

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMPS(I)</td>
<td>Amps</td>
<td>Conductor current through AXM at HIST(I)</td>
</tr>
<tr>
<td>TCI(I)</td>
<td>K</td>
<td>Coolant inlet temperature at HIST(I)</td>
</tr>
<tr>
<td>QINT(I)</td>
<td>W/m$^3$</td>
<td>Non-ohmic internal heating at HIST(I)</td>
</tr>
<tr>
<td>HIST(I)</td>
<td>s</td>
<td>Time (Only needed for TCAN)</td>
</tr>
<tr>
<td>MN</td>
<td></td>
<td>Number of time points in input time/temp/current profile</td>
</tr>
<tr>
<td>NCYCLES</td>
<td></td>
<td>Number of time cycles to follow</td>
</tr>
<tr>
<td>TMI</td>
<td>K</td>
<td>Magnet initial temperature (Only needed for TCAN)</td>
</tr>
<tr>
<td>DTP1</td>
<td>s</td>
<td>Initial time breakpoint step size</td>
</tr>
<tr>
<td>DTP2</td>
<td>s</td>
<td>Final time breakpoint step size</td>
</tr>
<tr>
<td>DTBRK</td>
<td>s</td>
<td>Time for change from DTP1 to DTP2</td>
</tr>
<tr>
<td>TPLON</td>
<td>s</td>
<td>Time to turn on plotter</td>
</tr>
<tr>
<td>TPRON</td>
<td>s</td>
<td>Time to turn on printout</td>
</tr>
<tr>
<td>HE</td>
<td>W/m$^2$-K</td>
<td>Effective cross-coil heat transfer coefficient; HE = 0 indicates no cross-coil heat transfer.</td>
</tr>
<tr>
<td>WIDTH</td>
<td>m</td>
<td>Width of conductor</td>
</tr>
<tr>
<td>RMAX</td>
<td>m</td>
<td>Outer radius of pancake coil</td>
</tr>
</tbody>
</table>

This data is only needed for cross-coil heat transfer. Code currently has crude algorithm that determines the nearest axial node in adjacent pancake for the double pancake design with inlet near outlet (as in ISX-B and TARA coils).
Table 2: Steady-state water-cooled copper test

<table>
<thead>
<tr>
<th>CASE 1</th>
<th>CASE 2</th>
<th>CASE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L$ (m)</td>
<td>18.3</td>
<td>5.</td>
</tr>
<tr>
<td>$A_m$ (cm$^2$)</td>
<td>1.</td>
<td>1.</td>
</tr>
<tr>
<td>$D$ (cm)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$T_{c,inlet}$ (K)</td>
<td>280.</td>
<td>280.</td>
</tr>
<tr>
<td>$p_{inlet}$ (MPa)</td>
<td>5.</td>
<td>5.</td>
</tr>
<tr>
<td>$I$ (kA)</td>
<td>1.</td>
<td>10.</td>
</tr>
<tr>
<td>$G_A_c$ (kg/s)</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>RESULTS:</strong></td>
<td>CCAN/TCAN/Empirical</td>
<td>CCAN/TCAN/Empirical</td>
</tr>
<tr>
<td>$T_{c,exit}$ (K)</td>
<td>287/287/289</td>
<td>338/338/330</td>
</tr>
<tr>
<td>$T_{m,exit}$ (K)</td>
<td>288/288/</td>
<td>357/359/</td>
</tr>
<tr>
<td>$Re$</td>
<td>21200/21000/21000</td>
<td>231000/236000/</td>
</tr>
<tr>
<td>$\Delta p$ (MPa)</td>
<td>1.27/1.28/1.22</td>
<td>3.54/3.50/4.5</td>
</tr>
<tr>
<td>$P_{dec}$ (kW)</td>
<td>3.0/3.0/</td>
<td>96/96/</td>
</tr>
<tr>
<td>$P_{pump}$ (kW)</td>
<td>0.1/0.1/</td>
<td>1.4/1.4/</td>
</tr>
</tbody>
</table>

Note: Square conductor cross-section; internal circular coolant channel; 100 RRR copper; no magnetic field; 100% pump hydraulic efficiency.
Figure 1: Transient cooldown of a thin body, initially at $T_{m0}$, placed in coolant at fixed temperature $T_c$. Parameters: $A_m = 1$ cm$^2$; $P_h = 3.5$ cm; $h \approx 1700$ W/m$^2$-K; $T_c = 70$ K; and $T_{m0} = 110$ K.
Figure 2: Long cryogenic $\text{gHe}$ cooled tubes at different inlet conditions.
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Figure 3: Cryogenic flow instability in $^4$He cooled current leads.