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HeFlow: A Program for Calculating Pressure and Temperature of Helium in Forced-Flow Superconductors

M. W. Keller

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HEFLOW: A PROGRAM FOR CALCULATING PRESSURE AND TEMPERATURE OF HELIUM IN FORCED-FLOW SUPERCONDUCTORS

Part 1: Numerical Solutions and Part 2: HeFlow User's Manual

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Part 1
NUMERICAL SOLUTIONS

ABSTRACT

HeFlow, a program to calculate the pressure and temperature of supercritical helium flowing in a heated channel, has been used to model the flow in the Westinghouse (WH) Large Coil Program (LCP) coil. The passage of the helium both at normal operating conditions and near the critical point has been shown to be isenthalpic to better than 1 or 2 parts in 1000. The effect of changing the sign of the Joule-Thomson (J-T) coefficient is discussed, and a useful approximation for temperature changes in helium flow is developed.

1. INTRODUCTION

Dresner[1] has shown that the hydrodynamic equations of continuity, momentum, and energy for the turbulent flow of a compressible fluid in a heated channel lead to the following relations:

$$\frac{dP}{dX} = -\frac{\frac{2f\rho}{D}\left(\frac{Cp}{\beta} + \frac{G^2}{\rho^2}\right) + \frac{\rho^2 \dot{q}}{G}}{\beta T - \frac{\rho C p B_T}{\beta} + \frac{\rho^2 C p}{G^2 \beta}} , \tag{1}$$

$$\frac{dT}{dX} = \frac{\frac{2f}{D}\left(\frac{\rho - G^2 B_T}{\rho \beta T} - 1\right) + \frac{\dot{q}\rho^2(\rho - G^2 B_T)}{G^3 \beta T}}{\beta + \frac{Cp\rho^2}{\beta T G^2}\left(1 - \frac{G^2 B_T}{\rho}\right)} . \tag{2}$$

These equations describe how pressure and temperature vary along a heated path filled with single-phase helium in steady-state flow. The solutions thus provide information important to the design of future superconductors cooled by forced flow of supercritical helium. One would especially like to know whether the temperature of the helium at any point exceeds the current-sharing temperature $T_{cs}\ (B, J)$ at that point.

The HeFlow program is designed to solve these two equations simultaneously to give the pressure and temperature of the fluid versus distance along the channel. Pressure and temperature at the inlet, mass flow rate, and heat load on the channel are assumed to be variables input by the user. The geometry of the flow path is assumed to be fixed. A library of functions called HEPROP, written by B. A. Hands,[2] provides the relevant properties of helium: ρ, C_p, β, and B_T. The only remaining variable necessary to evaluate Eqs. (1) and (2) is the friction factor, which is specific to the flow path. When this is known, the equations can be solved using a standard Runge-Kutta integrating routine.

2. MODELING THE WH LCP COIL

Data describing the WH coil are given in Table 1. The mass flux rate for a 120-m path in the WH coil can be found from the mass flow rate for the whole coil via the relation

$$G = \frac{\dot{m}}{54.76A} \quad ,$$

where $\dot{m}$ is in kg/s and the scaling factor of 54.76 is found from the ratios of the flows in different-length paths for a given pressure drop, which were provided by Westinghouse.[3]

Table 1. Westinghouse coil characteristics

$A = 88\ \mathrm{mm}^2 = 8.8 \times 10^{-5}\ \mathrm{m}^2$
$D = 0.4\ \mathrm{mm} = 4 \times 10^{-4}\ \mathrm{m}$
$L = 120\ \mathrm{m}$
Helium/void fraction = 32%
Type of cabling: $3^4 \times 6$
Number of strands = 486 (0.7-mm diam)
Conduit: 1.75-mm-thick stainless steel, square cross section with section with indium tape around cable

Friction factors for cable-in-conduit conductors have been investigated by Lue, Miller, and Lottin.[4] They found that friction factors for this type of conductor are 2 to 3 times the smooth-tube values in the turbulent flow regime and that the transition between laminar and turbulent flow is much less abrupt than in smooth tubes. Hooper[5] constructed the following correlation from Lue's data:

$$f = \exp(13.15Re^{-0.36} - 4.338) \quad .$$

It was noticed, however, that this correlation fit all sets of data except one, which had a distinctly higher friction factor and smaller helium/void fraction than the others. This was a cable of 7×3^3 insulated strands that was wrapped with Kapton tape and sheathed in a square conduit. Its helium/void fraction was 27.2%. Of the conductors examined by Lue et al., this was the one most like the conductor used in the WH coil for LCP.

Because the friction factor for three square cable-in-conduit conductors tested by Lue et al. appeared to depend inversely on void fraction, it was decided to make

a linear interpolation based on this parameter between Hooper's correlation and a hand-drawn fit of the 27.2% void conductor. Hooper's expression corresponds to a void fraction of about 50%, and from Table 1 the WH void fraction is 32%. Thus, the WH friction factor is about 79% of the way from Hooper's correlation to the hand-drawn fit. This gives

$$f = \exp(13.24 Re^{-0.36} - 3.977) \ .$$

Figure 1 shows plots of this interpolated result and, for comparison, the smooth-tube expressions.

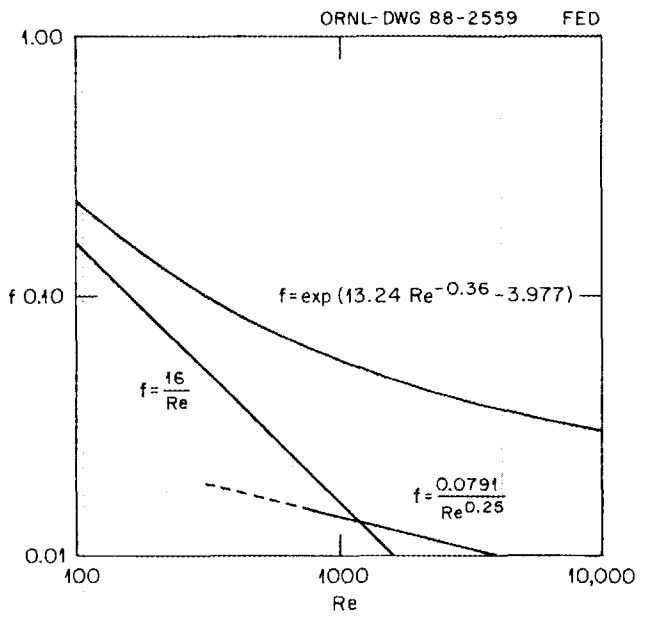

Fig. 1. Comparison of friction factors for the WH conductor and for a smooth tube.

3. RESULTS

3.1 ISENTHALPY

For purposes of approximation, the passage of helium is often assumed to be isenthalpic when there is no external heating. HeFlow was used to check the validity of this approximation. The results are given in Table 2, which shows the various helium properties at 5-m intervals along a 120-m length of WH conductor. It is apparent that the flow differs from isenthalpy by less than 1 part in 1000. Studies of

Table 2. Helium properties calculated using HeFlow for a 120-m length of WH conductor with no heat load ($\dot{m}$ = 190 g/s)

X (m)	P (atm)	T (K)	ρ (kg/m^3)	C_p (J/kg·K)	B_T (atm^{-1})	β (K^{-1})	H (J/kg)	Viscosity (N/s·m^2)	Re	f
0	12.9936	4.600	152.91	3093.46	9.87659×10^{-8}	0.0534612	16257.9	5.24665×10^{-6}	3005.98	0.03932
5	12.9013	4.616	152.63	3114.18	9.99576×10^{-8}	0.0540535	16258.3	5.22544×10^{-6}	3018.17	0.03928
10	12.8025	4.632	152.34	3134.98	1.01174×10^{-7}	0.0546532	16258.7	5.20430×10^{-6}	3030.43	0.03924
15	12.7037	4.647	152.06	3155.89	1.02416×10^{-7}	0.0552607	16259.1	5.18319×10^{-6}	3042.78	0.03919
20	12.6048	4.663	151.77	3176.89	1.03685×10^{-7}	0.0558762	16259.5	5.16213×10^{-6}	3055.19	0.03915
25	12.5057	4.678	151.47	3198.01	1.04981×10^{-7}	0.0565001	16260.0	5.14111×10^{-6}	3067.69	0.03911
30	12.4066	4.693	151.18	3219.23	1.06305×10^{-7}	0.0571327	16260.5	5.12012×10^{-6}	3080.26	0.03907
35	12.3075	4.708	150.89	3240.57	1.07658×10^{-7}	0.0577742	16261.0	5.09917×10^{-6}	3092.92	0.03902
40	12.2082	4.723	150.59	3262.02	1.09041×10^{-7}	0.0584250	16261.5	5.07824×10^{-6}	3105.66	0.03898
45	12.1088	4.738	150.29	3283.60	1.10455×10^{-7}	0.0590855	16262.0	5.05734×10^{-6}	3118.50	0.03894
50	12.0094	4.752	149.99	3305.31	1.11901×10^{-7}	0.0597560	16262.6	5.03647×10^{-6}	3131.42	0.03890
55	11.9098	4.767	149.68	3327.15	1.13380×10^{-7}	0.0604368	16263.1	5.01561×10^{-6}	3144.44	0.03885
60	11.8102	4.781	149.38	3349.13	1.14892×10^{-7}	0.0611284	16263.7	4.99478×10^{-6}	3157.55	0.03881
65	11.7105	4.795	149.07	3371.25	1.16440×10^{-7}	0.0618310	16264.3	4.97397×10^{-6}	3170.77	0.03877
70	11.6106	4.810	148.76	3393.52	1.18024×10^{-7}	0.0625452	16265.0	4.95316×10^{-6}	3184.09	0.03873
75	11.5107	4.823	148.45	3415.95	1.19645×10^{-7}	0.0632712	16265.6	4.93237×10^{-6}	3197.51	0.03868
80	11.4107	4.837	148.13	3438.53	1.21306×10^{-7}	0.0640095	16266.3	4.91158×10^{-6}	3211.05	0.03864
85	11.3105	4.851	147.82	3461.28	1.23006×10^{-7}	0.0647606	16266.9	4.89079×10^{-6}	3224.69	0.03860
90	11.2103	4.865	147.50	3484.20	1.24747×10^{-7}	0.0655249	16267.6	4.87001×10^{-6}	3238.45	0.03856
95	11.1099	4.878	147.17	3507.29	1.26531×10^{-7}	0.0663028	16268.3	4.84924×10^{-6}	3252.33	0.03851
100	11.0095	4.891	146.85	3530.57	1.28360×10^{-7}	0.0670948	16269.1	4.82845×10^{-6}	3266.33	0.03847
105	10.9089	4.904	146.52	3554.03	1.30234×10^{-7}	0.0679015	16269.8	4.80767×10^{-6}	3280.45	0.03843
110	10.8082	4.917	146.19	3577.69	1.32156×10^{-7}	0.0687232	16270.5	4.78687×10^{-6}	3294.70	0.03839
115	10.7074	4.930	145.86	3601.56	1.34127×10^{-7}	0.0695606	16271.3	4.76606×10^{-6}	3309.09	0.03834
120	10.6065	4.943	145.52	3625.59	1.36144×10^{-7}	0.0704123	16272.3	4.74530×10^{-6}	3323.56	0.03830

the enthalpy were also made near the critical point for helium: 5.2 K and 2.245 atm. The inlet conditions were chosen so that this point was reached near the end of the channel, and the enthalpy was found to be constant to within 1 or 2 parts in 1000.

3.2 JOULE-THOMSON INVERSION

The J-T coefficient is defined as the incremental change in temperature for a small change in pressure at constant enthalpy,

$$\mu = \left(\frac{\partial T}{\partial P}\right)_H \quad .$$

An important change occurs in the behavior of a fluid when μ changes sign. Figure 2 shows the isenthalpic inversion curve for helium (i.e., the locus of points where $\mu = 0$). If helium enters an unheated channel at some point (P_1, T_1) below the inversion line, where $\mu < 0$, a decrease in pressure will cause an increase in temperature. If at some point further down the channel the helium crosses the inversion line to a point such as (P_2, T_2), where $\mu > 0$, a decrease in pressure will cause a decrease in temperature. Thus, the helium may heat as it passes through the first part of the channel, reach a maximum as it crosses the inversion curve, and then cool as it flows through the rest of the channel.

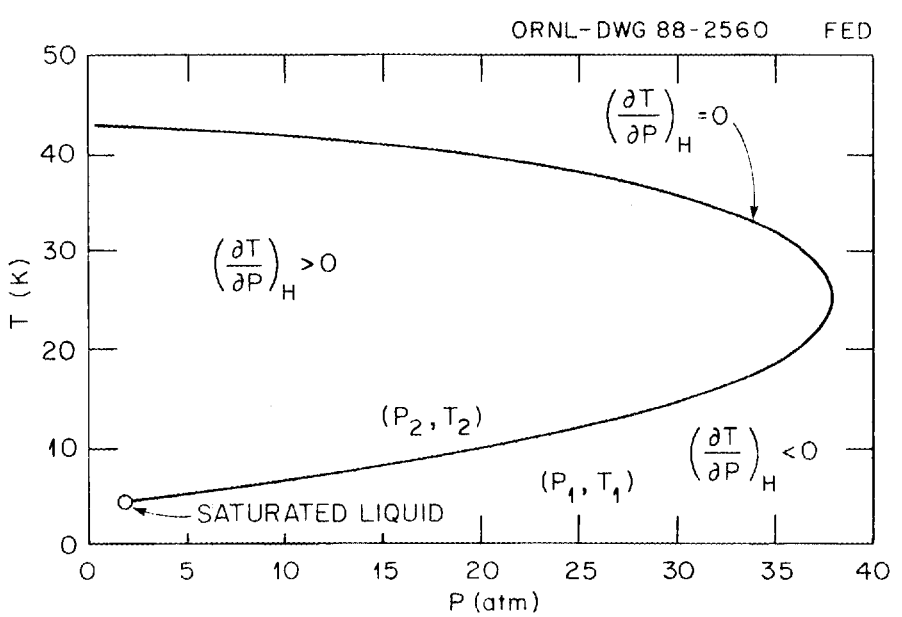

Fig. 2. Isenthalpic Joule-Thomson inversion curve for helium. Source: R. D. McCarty, NBS Technical Note 631, 1972, p. 18.

Figure 3 shows plots made with HeFlow for an isenthalpic flow where μ changes sign. Temperature and pressure at the point of maximum temperature lie on the inversion curve of Fig. 2.

When the flow is not isenthalpic, such as when there is nuclear or resistive heating of the conductor, J-T inversion still takes place, but the situation is complicated by the competing influence of the heat source. In some cases, the effect of μ changing signs will dominate and the helium will cool after reaching a maximum temperature. In other cases, the temperature will rise throughout the channel, although the slope may decrease where μ passes through zero. In general, a heat load will make it less likely that the temperature will reach a maximum before the end of the channel. Figure 4 shows the temperature distributions for helium starting at identical inlet conditions but with different heat loads distributed uniformly over the path.

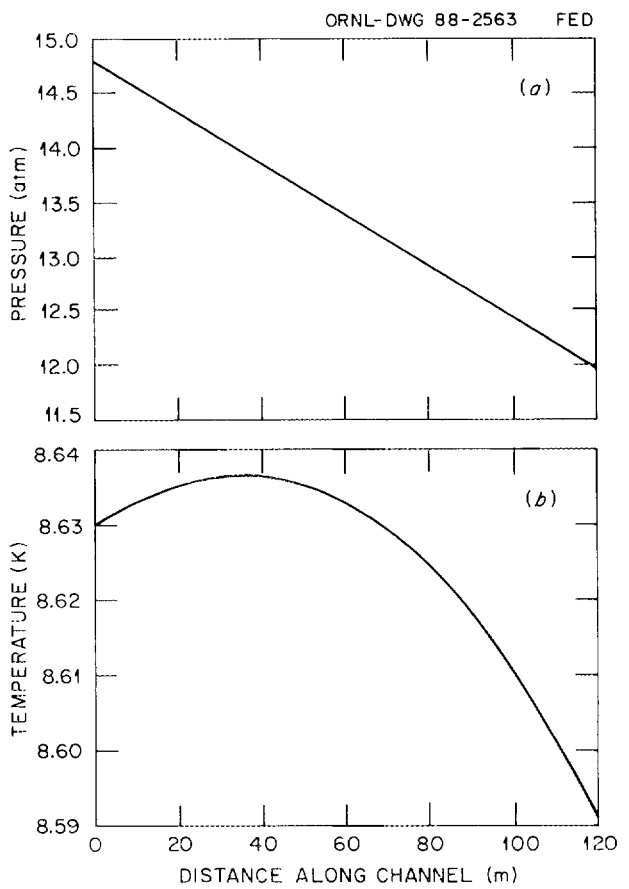

Fig. 3. (a) Pressure and (b) temperature of helium in an unheated channel ($\dot{m} = 100$ g/s).

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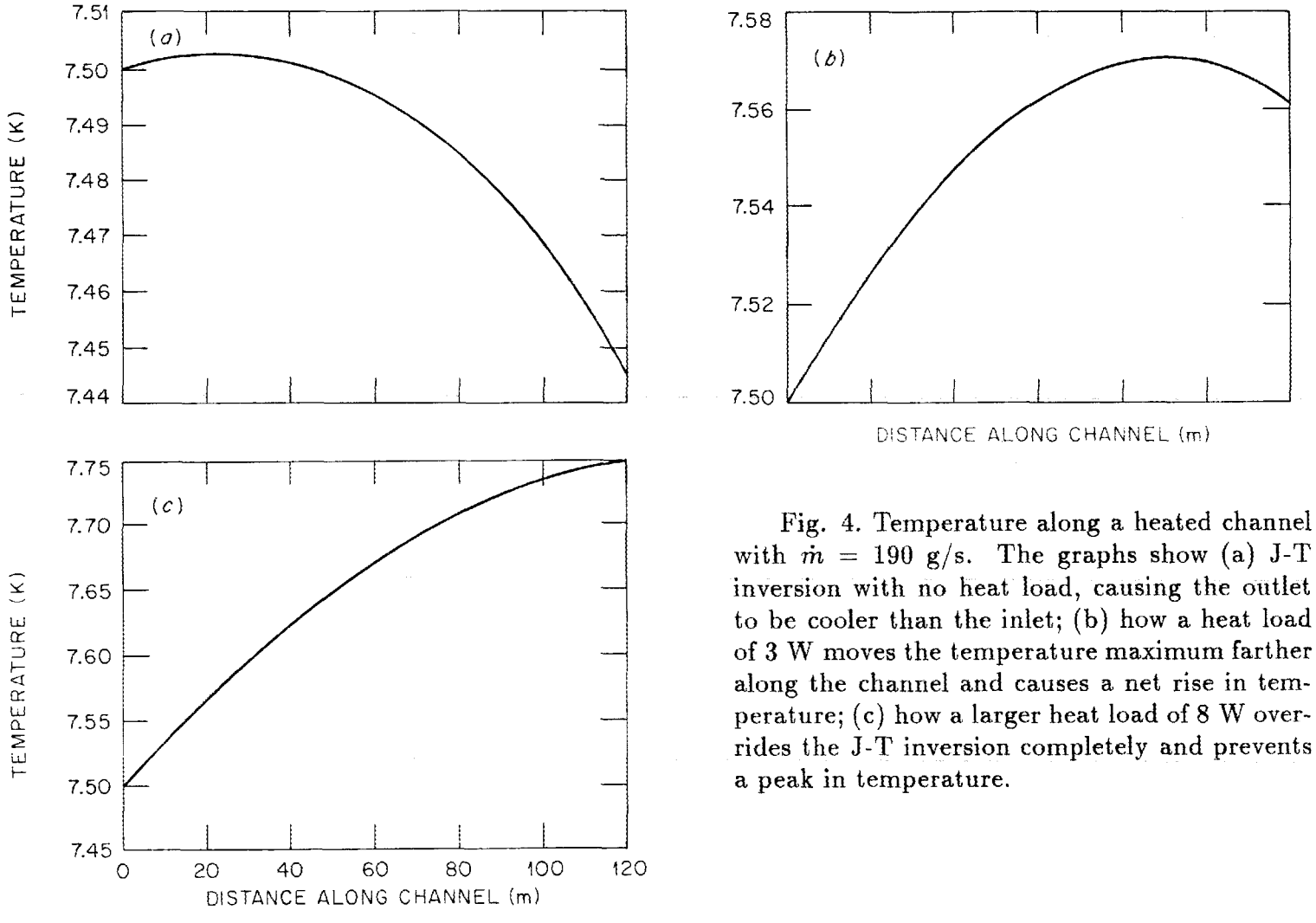

Fig. 4. Temperature along a heated channel with $\dot{m}$ = 190 g/s. The graphs show (a) J-T inversion with no heat load, causing the outlet to be cooler than the inlet; (b) how a heat load of 3 W moves the temperature maximum farther along the channel and causes a net rise in temperature; (c) how a larger heat load of 8 W overrides the J-T inversion completely and prevents a peak in temperature.

The cooling of helium when $\mu < 0$ is an approach that magnet designers may want to consider as a means of improving stability. Obviously a key design criterion is that the maximum temperature along the channel does not exceed the current-sharing temperature T_{cs} (B, J) at that point. By varying the inlet conditions for a given heat load, the temperature maximum can be located anywhere along the path, preferably in a low-field region. Since there is no curve such as Fig. 2 for nonisenthalpic flow, a program such as HeFlow is needed to show how the J-T effect may affect stability in various scenarios.

Normal operating conditions inside the WH coil are restricted to absolute pressures above about 10 atm and temperatures below about 5 K. In this range, μ is always negative, so the helium always heats up as the pressure drops. In some tests of the WH coil alone, however, the inlet temperature was as high as 8.3 K and the background heat loads were small. Given the test conditions for the WH test on March 26, 1987, and an estimated heat load of about 80 W for the whole coil, HeFlow predicts the temperature distribution shown in Fig. 5b. No sensors are available to check the temperature maximum inside the channel, but the outlet temperature as recorded by sensor TE2164 was about 0.2 K below the inlet (TE2163). This points to a temperature maximum somewhere inside the conductor, but without a reliable estimate of the heat load on that particular path, one cannot say where it is located.

3.3 A USEFUL APPROXIMATION

For quick estimations of temperature changes across a flow path, it is convenient to have an expression that can be evaluated without the use of a computer. If we consider the substitution of typical values into Eq. (2), we can obtain such an expression.

For $G = 20$ kg s^{-1} m^{-2}, $\rho = 150$ kg m^{-3}, $B_T = 4 \times 10^{-7}$ Pa^{-1}, $\beta = 0.1$ K^{-1}, $T = 4$ K, and $C_p = 3000$ J kg^{-1} K^{-1}, the term GB_T can be neglected when compared to ρ in three places, and $\rho C_p/\beta TG$ dominates β in the denominator. Thus, Eq. (2) can be written

$$\frac{dT}{dX} = \frac{\frac{2f}{D}\left(\frac{1}{\beta T} - 1\right) + \frac{\dot{q}\rho^3}{G^3\beta T}}{\frac{Cp\rho^2}{\beta TG^2}}$$

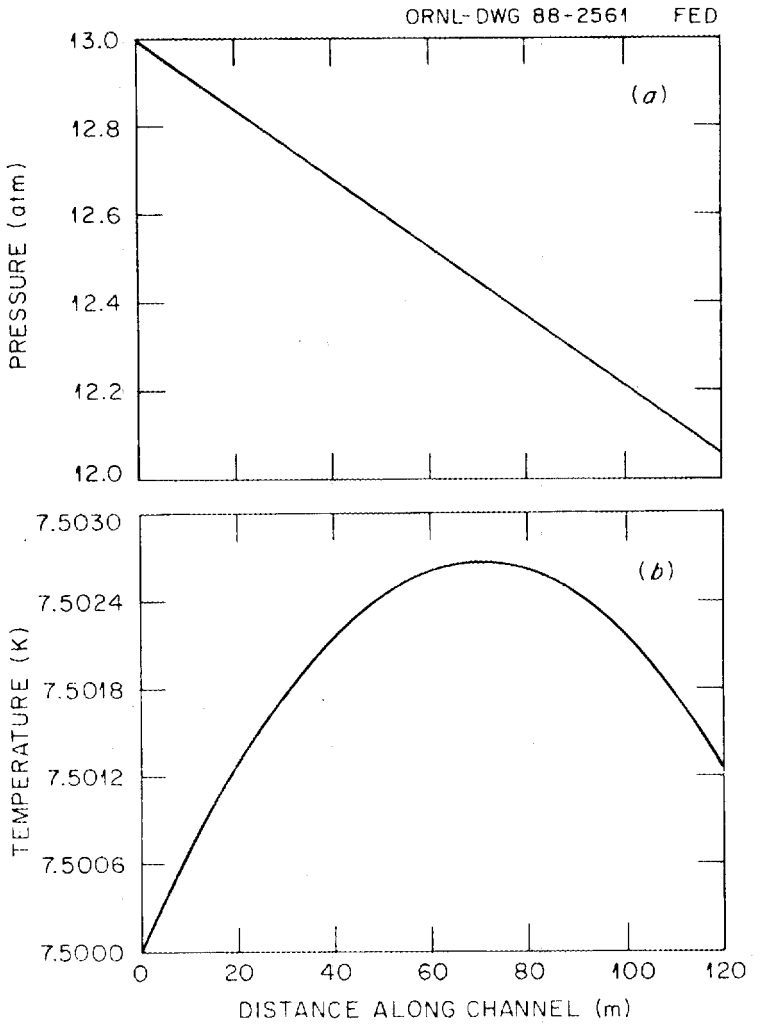

Fig. 5. (a) Pressure and (b) temperature in the WH conductor with $\dot{m} = 177$ g/s and a background heat load of 2 W on the channel (~84 W on the coil). These plots approximate conditions during the WH single-coil tests at high inlet temperature with $I = 800$ A.

$$= \frac{2fG^2}{\rho^2 D}\left(\frac{1-\beta T}{Cp}\right) + \frac{\dot{q}\rho}{GCp} \quad .$$

This neglect of terms has been checked with HeFlow very near the critical point and found to be wholly justified.

By using the identity $\mu = (\partial T/\partial P)_H = (\beta T - 1)/\rho Cp$, Eq. (3) becomes

$$\frac{dT}{dX} = \frac{-2fG^2}{\rho D}\mu + \frac{\dot{q}\rho}{GCp} \quad .$$

If we now assume that the enthalpy is approximately constant, we can write

$$\Delta T = \Delta P \mu + \frac{\dot{q} \rho L}{G C p} \tag{3}$$

for the temperature change across the conductor in steady-state flow. This approximation says the total temperature change is the sum of the isenthalpic change and the change due to the heat load on the conductor. The values given by Eq. (3) were checked against the values calculated by HeFlow, and agreement was good. Time limitations prevented a rigorous check, but for a 3-W heat load over the path the approximation gave values that were within a few tenths of a Kelvin, and for a 0.5-W heat load the agreement was within 0.05 K. This is shown by the data in Table 3.

Table 3. Comparison of temperature changes found by HeFlow and by the approximation in Eq. (3)[a]

T_{in} (K)	$\dot{m}$ (g/s)	Background power (W)	ΔT calculated by HeFlow (K)	$\Delta T = (\Delta T)_H + \frac{\rho \dot{q} L}{G C p}$ (K)
3	180	3.0	0.94	1.06
4	180	3.0	0.69	0.75
5	180	3.0	0.50	0.53
6	180	3.0	0.36	0.39
8	180	3.0	0.18	0.21
3	100	0.5	0.36	0.38
4	100	0.5	0.26	0.27
5	100	0.5	0.18	0.19
6	100	0.5	0.13	0.13
7	100	0.5	0.08	0.08

[a] $P_{in} = 13.0$ atm.

ACKNOWLEDGMENTS

I would like to extend my gratitude to all the LCP staff, who made this work a pleasant and rewarding experience. Special thanks go to Dan Fehling, who helped with programming difficulties, and to Jim Luton and Larry Dresner, who patiently listened and were a constant source of ideas and advice.

SYMBOLS

A = area of conductor available for helium flow (m^2)

$B_T = \frac{-1}{V}\left(\frac{\partial V}{\partial P}\right)_T$ = isothermal compressibility (atm^{-1})

C_p = specific heat at constant pressure (J/kg·K)

D = hydraulic diameter (m)

f = friction factor

G = mass flux rate ($kg/m^2 \cdot s$)

H = enthalpy (J/kg)

L = length of channel (m)

$\dot{m}$ = mass flow rate (kg/s)

P = pressure (atm)

$\dot{q}$ = specific heating rate (W/kg)

Re = Reynold's number

T = temperature (K)

X = distance along channel (m)

$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$ = isobaric expansivity (K^{-1})

$\mu = \left(\frac{\partial T}{\partial P}\right)_H$ = Joule-Thomson coefficient

ρ = density (kg/m^3)

REFERENCES

1. L. Dresner, Oak Ridge National Laboratory, "Calorimetric Measurement of Pulse Losses in Force-Cooled Coils," personal communication, June 30, 1983.
2. B. A. Hands, *HEPROP—A Computer Programme for the Thermodynamic and Thermophysical Properties of Helium*, 2nd ed., 1975.
3. *LCP Detailed Design and Analyses Report*, Vol. II, Part 4, p. 3-734, Westinghouse Electric Corporation, March 31, 1980.
4. J. W. Lue, J. R. Miller, and J. C. Lottin, "Pressure Drop Measurements on Forced Flow Cable Conductors," *IEEE Trans. Magn.*, **MAG-15**: 53–55 (1979).
5. R. J. Hooper, Fusion Engineering Design Center, personal communication, March 5, 1984.

Part 2
HEFLOW USER'S MANUAL

1. INTRODUCTION

1.1 PURPOSE

HeFlow was specifically designed to calculate the pressure and temperature of supercritical helium flowing through a 120-m path of cable-in-conduit conductor in the Westinghouse (WH) Large Coil Program (LCP) coil. With a few modifications, however, it can be readily adapted to more general physical situations.

1.2 GENERAL THEORY

The conservation equations for a compressible fluid in turbulent flow through a heated channel can be transformed to yield the following:[1]

$$\frac{dP}{dX} = -\frac{\frac{2f}{D}\left(\frac{\rho C_P}{\beta} + \frac{G^2}{\rho}\right) + \frac{\rho^2 \dot{q}}{G}}{\beta T - \frac{\rho C_P}{\beta}\left(B_T - \frac{\rho}{G^2}\right)} ,$$

$$\frac{dT}{dX} = \frac{\frac{2f}{D}\left(\frac{\rho - G^2 B_T}{\rho \beta T} - 1\right) + \frac{\rho^2 \dot{q}}{G \beta T}\left(\frac{\rho}{G^2} - B_T\right)}{\beta + \frac{\rho C_P}{\beta T}\left(\frac{\rho}{G^2} - B_T\right)} .$$

HeFlow solves these equations iteratively using a standard second-order Runge-Kutta integrating routine. If $y\prime = f(x, y, z)$ and $z\prime = g(x, y, z)$, then

$$y_{k+1} = y_k + \frac{j}{2}\{f(x_k,y_k,z_k) + f[x_k + j,\, y_k + jf(x_k,y_k,z_k),\, z_k + jg(x_k,y_k,z_k)]\} ,$$

$$z_{k+1} = z_k + \frac{j}{2}\{g(x_k,y_k,z_k) + g[x_k + j,\, y_k + jf(x_k,y_k,z_k),\, z_k + jg(x_k,y_k,z_k)]\} .$$

A library of functions called HEPROP, written by Hands,[2] is used to find the necessary helium properties.

1.3 AGII ROUTINES

HeFlow uses Tektronix AGII plotting routines to display pressure and temperature versus distance along the channel. These routines are explained in detail in the Tektronix manual, and a summary of the most commonly used routines is available on the VAX by typing HELP and then @FED_HELP. Alternative ways of plotting the data are discussed in Sect. 3.

2. RUNNING HEFLOW

HeFlow prompts the user for inlet pressure and temperature, mass flow rate, and background and resistive heat loads on the conductor. Each prompt gives the correct units in parentheses and a default value in brackets. To use the default values, the user simply presses ⟨RETURN⟩. If a value for the resistive heat is specified, the user is prompted for the coordinates along the channel at which the resistive zone begins and ends.

After all data have been entered, the user is asked whether he or she wants to store the helium properties in a file. If the reply is "yes," the user is prompted for the interval between points at which the data are sent to the file. This interval is the number of iterations between each "WRITE" command. If the the user chooses 5, for example, the file will contain the helium properties at every 5 m of channel length, since the iteration increment is 1.0 m. The interval must be a whole number.

NOTE: *All numerical inputs must include a decimal point.*

After completing all computations, HeFlow prints the values of all numerical input data as well as the outlet pressure, temperature, and velocity. For normal flow rates (around 180 g/s), the outlet velocity differs from the average by less than 0.5 cm/s. HeFlow then plots pressure and temperature versus distance on separate grids. Section 3 discusses ways of plotting the data in other configurations.

Upon close inspection, it becomes apparent that the point of intersection of the plot with the grid line marking the end of the channel does not agree exactly with the printed value for the outlet. The AGII plotting routines appear to be going one increment past the end of the channel, because the final plotted pressure is slightly low and the final plotted temperature is slightly high (unless the temperature has reached a maximum before the outlet).

The reason for this discrepancy remains a mystery, but the consequence is that the plots should not be used to determine the outlet pressure or temperature. The printed values are the only reliable source of this information. The plots are still useful, however, in determining maximum values and in quickly assessing qualitative changes along the channel.

The plots are stored in a file called TKF_HEFLOW.TKF. The printed table of helium properties is stored in FOR001.DAT.

3. MODIFICATIONS

By changing the parameter statements that define length, area, and hydraulic diameter and by using appropriate definitions for mass flux and friction factor, HeFlow can be adapted to various flow situations. Since Hands' HEPROP functions are valid over the range of about 2 K to 1700 K and up to about 100 MPa, HeFlow may also be used to study the flow of subcritical helium as long as the flow is single-phase.

The AGII plotting routines allow the data to be displayed in several different ways. The following commands can be used to plot pressure versus temperature:

```
CALL BINITT
CALL CHECK (Temp, Press)
CALL DSPLAY (Temp, Press)
CALL FINITT (0, 700)
```

The following commands can be used to plot both pressure and temperature on the same grid:

```
CALL BINITT
CALL CHECK (Dist, Press)
CALL DSPLAY (Dist, Press)
CALL DINITY
CALL YLOCRT(0)
CALL CHECK (Dist, Temp)
CALL DSPLAY (Dist, Temp)
CALL FINITT (0, 700)
```

These commands can be inserted immediately after the commands that plot the temperature data in the subroutine PLOT (see listing).

4. COMPUTATION AND PROGRAMMING NOTES

This section contains documentation and explanations of various steps in the program that are not given in the program listing because of limited space.

4.1 ITERATION INCREMENT

The iteration increment j is set to 1.0 by a parameter statement. This means that the program effectively makes a new evaluation of the helium properties at each meter along the flow path. Changing j to 0.5 changes the results of the computations only after the fifth decimal place, so a finer interval will not increase the accuracy of the integrating routine appreciably. Changing the interval does, however, provide a convenient way of obtaining a table with more frequent values of the helium properties. For example, an interval of 0.5 allows the user to create a table with the helium properties given every half meter.

4.2 MASS FLUX CALCULATION

The mass flux rate for a single channel in HeFlow is specific to the WH coil. For a 120-m path, it is given by

$$G = \frac{\dot{m}}{54.76A} \quad ,$$

where $\dot{m}$ is in g/s. The scaling factor of 54.76 was determined by considering the ratios of the flows through channels of different lengths for a fixed pressure drop. These ratios were provided by Westinghouse.[3]

4.3 DATA STORAGE ARRAYS

To use the AGII plotting routines, the data to be plotted must be stored in an array in which the first element contains the number of points to be plotted. The arrays are initialized to 10,000 elements but can be expanded if $L/j > 10,000$.

Note that array element i contains the pressure, temperature, or distance at $X = i - 1$.

4.4 UNITS

The HEPROP functions require inputs in SI units, so all variables are converted to SI units before they enter the iteration loop. The pressure plot uses units of atmospheres to facilitate comparisons with other data. The table of helium properties is in SI units except for pressure, which is again in atmospheres.

4.5 FRICTION FACTOR

The friction factor is specific to the WH coil. It was found by a linear interpolation based on helium/void fraction between two curves drawn to fit friction factor data for square cable-in-conduit conductors gathered by Lue, Miller, and Lottin.[4] This interpolation results in the expression

$$f = \exp(13.24 Re^{-0.36} - 3.977) \quad ,$$

where $Re = \frac{\rho v D}{\mu}$.

For smooth tubes, the friction factor is given by the Blasius relation,

$$f = \frac{0.0791}{Re^{0.25}} \quad .$$

4.6 RESISTIVE HEAT DISTRIBUTION

If the user specifies a value for the resistive heat load in the conductor, he or she is asked to also give the boundaries of the resistive zone, $X1$ and $X2$. The resistive heat contributes to the specific heating rate of the helium, $\dot{q}$, only within this zone. The volume used to determine the resistive contribution to $\dot{q}$ is simply the total volume of the channel times the fraction of resistive channel, $(X1 - X2)/L$.

4.7 CREATING THE OUTPUT FILE

The Tektronix AGII routines for labeling plots will accept only strings as arguments. Since these routines are used to write the input and output data into TKF_HELFOW.TKF, the data must be converted to string form. This is accomplished by using the ENCODE statement, which is explained in the VAX FORTRAN manual. The encoded strings are then concatenated with an identifying string and written into the file by the AGXXMHS subroutines (see listing in Sect. 5).

5. LISTING OF HEFLOW

The following pages contain the HeFlow program listing and description.

```
PROGRAM HeFlow

*****************************************************************************
*                                                                           *
*       Author.................................Mark W. Keller              *
*       Written................................7-1Ø-87                     *
*       Last Revised...........................8-28-87                     *
*                                                                           *
*****************************************************************************

*****************************************************************************
*                                                                           *
*               This program is designed to compute the temperature and     *
*       pressure of turbulent, supercritical helium in steady-state flow    *
*       through a heated channel.                                           *
*                                                                           *
*               The equations for continuity, momentum, and energy for      *
*       a compressible fluid in turbulent flow yield a coupled pair of      *
*       first-order differential equation describing pressure and           *
*       temperature.  This program solves these equations using a second-   *
*       order Runge-Kutta integrating routine.                              *
*                                                                           *
*               The program will plot pressure and temperature versus       *
*       distance using the Tektronix AGII plotting routines.  The plots     *
*       will appear in a file labeled TKF_HEFLOW.TKF.  The user may also    *
*       choose to have the properties of the helium printed in table form.  *
*       In this case an additional file labeled FORØØ1.DAT will contain the *
*       table.                                                              *
*                                                                           *
*               A library of subprograms called HEPROP, written by B.A.     *
*       Hands, is used to find the relevant properties of helium for        *
*       each iteration.  The functions which are used are the following:    *
*                                                                           *
*               DFUN (P, T)         Density at pressure and temperature.    *
*               HFUN (Rho, T)       Enthalpy at density and temperature.    *
*               VISC (Rho, T)       Viscosity at density and temperature.   *
*               CP (Rho, T)         Isobaric specific heat at density       *
*                                      and temperature.                     *
*               DPDD (Rho, T)       Rate of change of pressure with         *
*                                      density at density and temperature.  *
*               DPDT (Rho, T)       Rate of change of pressure with         *
*                                      temperature at density and           *
*                                      temperature.                         *
*                                                                           *
*       These routines require inputs in SI units.                          *
*                                                                           *
*****************************************************************************
```

```
*******************   Variable Dictionary   **********************************

        IMPLICIT NONE

*  Input variables
        REAL   P_in, T_in              ! Inlet pressure and temperature (atm)
        REAL   dmdt                    ! Helium flow rate through coil (g/s)
        REAL   Back_Pow                ! Background heat load (W)
        REAL   Res_Pow                 ! Resistive heat load (W)
        REAL   X1, X2                  ! Limits of resistive heating zone (m)
        LOGICAL  Print_Table           ! True is user wants to print table
        INTEGER  s                     ! Distance between points in table (m)

*  Internal variables
        INTEGER  I                     ! Loop counter
        INTEGER  Num                   ! Number of points to be plotted

        REAL   X                       ! Distance along channel (m)
        REAL   P, T                    ! Pressure and temperature in channel (Pa, K)
        REAL   Length                  ! Length of heated channel (m)
        REAL   A                       ! Area available for helium flow (m**2)
        REAL   V                       ! Volume of channel (m**3)
        REAL   D                       ! Hydraulic diameter of channel (m)
        REAL   G                       ! Mass flux rate (kg s**-1 m**-2)
        REAL   Veloc                   ! Velocity of helium (m/s)
        REAL   Re                      ! Reynolds number
        REAL   f                       ! Friction factor
        REAL   Rho                     ! Helium density (kg m**-3)
        REAL   Cp1                     ! Specific heat at constant pressure (J/kg-K)
        REAL   H                       ! Enthalpy (J/kg)
        REAL   Vis                     ! Viscosity (N s m**-2)
        REAL   Bt                      ! Isothermal compressibility (1/Pa)
        REAL   Bp                      ! Isobaric expansivity (1/K)
        REAL   dqdt                    ! Specific heating rate of helium (W/kg)
        REAL   j                       ! Iteration increment
        REAL   K, L, M, N              ! Storage locations for partial evaluations of P and T

        REAL Press(0:10000)            ! Array to hold values of P
        REAL Temp(0:10000)             ! Array to hold values of T
        REAL Dist(0:10000)             ! Array to hold values of X

        REAL dPdX                      ! Function
        REAL dTdX                      ! Function

        PARAMETER (j = 1.0)
        PARAMETER (Length = 120.0)
        PARAMETER (D = 0.0004)
        PARAMETER (A = 8.8E-5)
        PARAMETER (V = 8.8E-5 * 120.0)
```

```
*************************   Main Program   ***********************************

      CALL Input_Data (P_in, T_in, dmdt, Back_Pow, Res_Pow,
     $                 X1, X2, Print_Table, s)

      G = dmdt / (1000*A*54.75)    ! Convert mass flow rate to kg/s and
                                   ! calculate mass flux rate per channel
      Num = Length/j + 1
      Press(0) = Num               ! First element in each array must be the
      Temp(0) = Num                ! number of points to be plotted
      Dist(0) = Num

      X = 0                        ! Start at channel inlet

      Press(1) = P_in              ! First data point is at channel inlet
      Temp(1) = T_in
      Dist(1) = X

      P = P_in * 1.013E5           ! Initialize P and T to inlet conditions
      T = T_in                     ! (Pressure must be converted to Pa)

      IF (Print_Table) THEN        ! Print table heading and first line of data

         OPEN (UNIT = 1, STATUS = 'NEW')
         WRITE (1,10) 'X', 'P', 'T', 'Rho', 'Cp', 'Bt', 'Bp',
     $          'H', 'Vis', 'Re', 'f'
10       FORMAT (7X,A1,9X,A1,9X,A1,7X,A3,7X,A2,9X,A2,13X,A2,
     $           13X,A1,10X,A3,12X,A2,9X,A1)
         WRITE (1,*)
         CALL Heprop (P, T, Rho, Cp1, Bt, Bp, H, Vis)
         CALL Friction_Factor (T, G, Rho, D, Re, f, Veloc)
         WRITE (1,100) X, P_in, T_in, Rho, Cp1, Bt, Bp, H,
     $          Vis, Re, f
      END IF

      DO  I = 2, Num               ! Loop to calculate successive values of P and T

         X = X + j

         CALL HeProp (P, T, Rho, Cp1, Bt, Bp, H, Vis)
         CALL Heating_Rate (X, Back_Pow, Res_Pow, Rho,
     $          V, X1, X2, Length, dqdt)
         CALL Friction_Factor (T, G, Rho, D, Re, f, Veloc)
         K = dPdX (T, Rho, Cp1, D, f, G, Bt, Bp, dqdt)
         L = dTdX (T, Rho, Cp1, D, f, G, Bt, Bp, dqdt)
         CALL HeProp (P + j*K, T + j*L, Rho, Cp1, Bt, Bp, H, Vis)
         CALL Heating_Rate (X + j, Back_Pow, Res_Pow, Rho,
     $          V, X1, X2, Length, dqdt)
         CALL Friction_Factor (T + j*L, G, Rho, D, Re,
     $          f, Veloc)
         M = dPdX (T + j*L, Rho, Cp1, D, f, G, Bt, Bp, dqdt)
         N = dTdX (T + j*L, Rho, Cp1, D, f, G, Bt, Bp, dqdt)
```

```
         P = P + Ø.5*j*(K + M)
         T = T + Ø.5*j*(L + N)

         Press(I) = P/1.Ø13E5      ! Convert pressure back to atm and store
         Temp(I) = T               ! values in arrays
         Dist(I) = X

         IF (Print_Table .AND. MOD(I-1,s) .EQ. Ø) THEN    ! Write helium properties into file
            WRITE (1,1ØØ) X, P/1.Ø13E5, T, Rho, Cpl, Bt, Bp, H,
     $              Vis, Re, f
         END IF

      END DO

1ØØ   FORMAT (F1Ø.2,F1Ø.4,F1Ø.3,2F1Ø.2,4E14.6,F1Ø.2,F1Ø.5)
      IF (Print_Table) THEN
         CLOSE (UNIT = 1)
      END IF
      CALL Plot (Press, Temp, Dist, P_in, T_in, dmdt, Back_Pow,
     $            Res_Pow, Veloc, Press(Num), Temp(Num))

      END

************************   Subprograms   ************************************

      SUBROUTINE Input_Data (P_in, T_in, dmdt, Back_Pow, Res_Pow,
     $                       X1, X2, Print_Table, s)

         INTEGER ILEN                  ! Length of input string
         CHARACTER C
         LOGICAL PRINT_TABLE
         INTEGER s
         REAL n                        ! Dummy input

         PRINT *, 'Inlet pressure? (atm) [ 13.Ø ]'
         READ (*, 1Ø) ILEN, P_in
            IF (ILEN .EQ. Ø) THEN
              P_in = 13.Ø
            END IF
         PRINT *, 'Inlet temperature? (K) [ 4.Ø ]'
         READ (*, 1Ø) ILEN, T_in
            IF (ILEN .EQ. Ø) THEN
              T_in = 4.Ø
            END IF
         PRINT *, 'Mass flow rate? (g/s) [ 18Ø.Ø ]'
         READ (*, 2Ø) ILEN, dmdt
            IF (ILEN .EQ. Ø) THEN
              dmdt = 18Ø.Ø
            END IF
```

```
      PRINT *, 'Background heat load? (W) [ Ø.Ø ]'
      READ (*, 2Ø) ILEN, Back_Pow
         IF (ILEN .EQ. Ø) THEN
           Back_Pow = Ø.Ø
         END IF
      PRINT *, 'Resistive heat load? (W) [ Ø.Ø ]'
      READ (*, 2Ø) ILEN, Res_Pow
         IF (ILEN .EQ. Ø) THEN
           Res_Pow = Ø.Ø
         ELSE
Ø5         PRINT *, 'Limits of resistive zone...'
           PRINT *, 'X1 ?  '
           READ (*, 3Ø) X1
           PRINT *, 'X2 ?  '
           READ (*, 3Ø) X2
           IF (X2 .LE. X1) THEN
              PRINT *, 'Invalid entry'
              GOTO Ø5
           END IF
         END IF
      PRINT *, 'Send table of helium values to file? (y or n)'
      READ (*,4Ø) C
         IF (C .EQ. 'Y' .OR. C .EQ. 'y') THEN
           Print_Table = .TRUE.
           PRINT *, 'Distance between values? [ 1.Ømm ]'
           READ (*, 1Ø) ILEN, n
           IF (ILEN .EQ. Ø) THEN
              s = 1
           ELSE
              s = INT(n)
           END IF
         ELSE
           Print_Table = .FALSE.
         END IF
      PRINT *, 'Working...'

1Ø    FORMAT (Q, F5.2)
2Ø    FORMAT (Q, F7.3)
3Ø    FORMAT (F6.2)
4Ø    FORMAT (A1)

   RETURN
   END

   SUBROUTINE HeProp (P, T, Rho, Cpl, Bt, Bp, H, Vis)

      Rho = DFUN(P, T)
      H = HFUN(Rho, T)
      Vis = VISC(Rho, T)
      Cpl = CP(Rho, T)
      Bt = 1 / (Rho * DPDD(Rho, T))
      Bp = Bt * DPDT(Rho, T)
```

```
      RETURN
      END

      SUBROUTINE Heating_Rate (X, Back_Pow, Res_Pow, Rho,
     $                         V, X1, X2, Length, dqdt)
      REAL Length

         IF (X.LT.X1 .OR. X.GT.X2) THEN      ! X is not in the resistive zone
            dqdt = Back_Pow/(Rho * V)
         ELSE
            dqdt = Back_Pow/(Rho * V)
     $            + Res_Pow/(Rho * V * (X2-X1)/Length)
         END IF

      RETURN
      END

      SUBROUTINE Friction_Factor (T, G, Rho, D, Re, f, Veloc)

            Veloc = G / Rho
            Re = Rho * Veloc * D / VISC(Rho, T)
            f = EXP(13.24 * Re**-0.36 - 3.977)

      RETURN
      END

      REAL FUNCTION dPdX (T, Rho, Cpl, D, f, G, Bt, Bp, dqdt)

         REAL  W                    ! Storage location for partial evaluation of dPdX

            W = Bp*T - (Bt - Rho/(G*G)) * Rho*Cpl/Bp

            dPdX = - ( 2*f * (Rho*Cpl/Bp + G*G/Rho)/D + Rho*Rho*dqdt/G )/W

      RETURN
      END

      REAL FUNCTION dTdX (T, Rho, Cpl, D, f, G, Bt, Bp, dqdt)

         REAL Y, Z                  ! Storage locations for partial evaluations of dTdX

            Y = dqdt*Rho*Rho * (Rho/(G*G) - Bt)/(G*Bp*T)

            Z = Bp + Rho*Cpl * (Rho/(G*G) - Bt)/(Bp*T)

            dTdX = ( 2*f * ((Rho - G*G*Bt)/(Rho*Bp*T) - 1)/D + Y )/Z
```

```
      RETURN
      END

      SUBROUTINE Plot (Press, Temp, Dist, P_in, T_in, dmdt, Back_Pow,
     $          Res_Pow, Veloc, P_out, T_out)

         CHARACTER I                          ! Dummy input
         CHARACTER*70 PSTRING, TSTRING, MSTRING, BSTRING, RSTRING,
     $                VSTRING, POUT, TOUT

*        Assign character strings
            ENCODE (70, 10, PSTRING) P_in
10          FORMAT (F8.2)
            PSTRING = 'Inlet pressure (atm) ='//PSTRING
            ENCODE (70, 20, TSTRING) T_in
20          FORMAT (F6.2)
            TSTRING = 'Inlet temperature (K) =  '//TSTRING
            ENCODE (70, 30, MSTRING) dmdt
30          FORMAT (F8.2)
            MSTRING = 'Mass flow rate (g/s) ='//MSTRING
            ENCODE (70, 40, BSTRING) Back_Pow
40          FORMAT (F7.2)
            BSTRING = 'Background heat load (W) = '//BSTRING
            ENCODE (70, 50, RSTRING) Res_Pow
50          FORMAT (F7.2)
            RSTRING = 'Resistive heat load (W) ='//RSTRING
            ENCODE (70, 60, VSTRING) Veloc
60          FORMAT (F7.3)
            VSTRING = 'Helium velocity (m/s) ='//VSTRING
            ENCODE (70, 70, POUT) P_out
70          FORMAT (F8.2)
            POUT = 'Outlet pressure (atm) ='//POUT
            ENCODE (70, 80, TOUT) T_out
80          FORMAT (F6.2)
            TOUT = 'Outlet temperature ='//TOUT

*        Open file and initialize screen
            CALL OPNTKF ('TKF_Heflow')
            CALL INITT (0)
            CALL BINITT

*        Print strings
            CALL AGXXMHS (3, 692, PSTRING)
            CALL AGXXMHS (3, 628, TSTRING)
            CALL AGXXMHS (3, 564, MSTRING)
            CALL AGXXMHS (3, 500, BSTRING)
            CALL AGXXMHS (3, 436, RSTRING)
            CALL AGXXMHS (3, 372, VSTRING)
            CALL AGXXMHS (3, 308, POUT)
            CALL AGXXMHS (3, 244, TOUT)
```

```
            CALL AGXXCPT (5, 'PRESS RETURN TO CONTINUE')
            READ (*,90) I
            CALL NEWPAG

*        Print labels
            CALL AGXMVS (3, 500, 'Pressure  atm')
            CALL AGXCHS ('Distance along channel (m)')
*        Plot pressure data
            CALL CHECK (Dist, Press)
            CALL DSPLAY (Dist, Press)

            CALL AGXXCPT (5, 'PRESS RETURN TO VIEW NEXT GRAPH')
            READ (*,90) I
            CALL NEWPAG

*        Reinitialize screen
            CALL BINITT

*        Print labels
            CALL AGXMVS (3, 500, 'Temperature  K')
            CALL AGXCHS ('Distance along channel (m)')

*        Plot temperature data
            CALL CHECK (Dist, Temp)
            CALL DSPLAY (Dist, Temp)
*           CALL FINITT (0, 700)

            CALL AGXXCPT (5, 'PRESS RETURN TO EXIT PROGRAM')
            READ (*,90) I
90          FORMAT (A1)

            CALL INITT (0)
            CALL TKFOFF
            CALL FINITT (0, 700)
            CALL VT$TPMODE

      RETURN
      END
```

SYMBOLS

A = area of conductor available for helium flow (m^2)

$B_T = \frac{-1}{V}\left(\frac{\partial V}{\partial P}\right)_T$ = isothermal compressibility (atm^{-1})

C_p = specific heat at constant pressure (J/kg·K)

D = hydraulic diameter (m)

f = friction factor

G = mass flux rate ($kg/m^2 \cdot s$)

H = enthalpy (J/kg)

j = iteration increment

L = length of channel (m)

$\dot{m}$ = mass flow rate (kg/s)

P = pressure (atm)

$\dot{q}$ = specific heating rate (W/kg)

Re = Reynold's number

T = temperature (K)

v = velocity (m/s)

X = distance along channel (m)

$X1, X2$ = beginning and end of resistive zone (m)

$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$ = isobaric expansivity (K^{-1})

μ = viscosity ($N/s \cdot m^2$)

ρ = density (kg/m^3)

REFERENCES

1. L. Dresner, Oak Ridge National Laboratory, "Calorimetric Measurement of Pulse Losses in Force-Cooled Coils," personal communication, June 30, 1983.
2. B. A. Hands, *HEPROP—A Computer Programme for the Thermodynamic and Thermophysical Properties of Helium*, 2nd ed., 1975.
3. *LCP Detailed Design and Analyses Report*, Vol. II, Part 4, p. 3-734, Westinghouse Electric Corporation, March 31, 1980.
4. J. W. Lue, J. R. Miller, and J. C. Lottin, "Pressure Drop Measurements on Forced Flow Cable Conductors," *IEEE Trans. Magn.*, **MAG-15**: 53–55 (1979).

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