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NASA Lewis Steady-State Heat Pipe Code Architecture

Final Report

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Abstract

NASA Glenn Research Center (GRC) has developed the LERCHP code. The PC-based LERCHP code can be used to predict the steady-state performance of heat pipes, including the determination of operating temperature and operating limits which might be encountered under specified conditions. The code contains a vapor flow algorithm which incorporates vapor compressibility and axially varying heat input. For the liquid flow in the wick, Darcy's formula is employed. Thermal boundary conditions and geometric structures can be defined through an interactive input interface. A variety of fluid and material options as well as user defined options can be chosen for the working fluid, wick, and pipe materials. This report documents the current effort at GRC to update the LERCHP code for operating in a Microsoft Windows (Microsoft Corporation) environment. A detailed analysis of the model is presented. The programming architecture for the numerical calculations is explained and flowcharts of the key subroutines are given.

Nomenclature

Latin Symbols

a Busse velocity profile parameter
A_v cross section area of vapor passage
A_w cross section area of wick
h enthalpy
m mass
$\dot{m}$ mass flow rate
K wick permeability
p pressure
q total axial heat input
R radius of vapor flow
R_g gas constant
Re Reynolds number
T temperature
u radial velocity
v axial velocity

*Distinguished Research Associate.

z axial coordinate
ρ density
μ dynamic viscosity
σ surface tension

Subscripts

A adiabatic section
c center or critical dimension
C condenser
E evaporator
g vapor
l liquid
m area average
r radial parameter
R vapor-liquid interface
M vapor mean

1.0 Introduction

The heat pipe is a highly efficient, nearly isothermal, passive two-phase heat transfer device. For the purpose of designing and optimizing heat pipe based thermal systems with applications in space power conversion technologies, NASA Glenn Research Center has developed the LERCHP code. This report is the updated documentation of it. For earlier versions, see References 1 and 2.

The PC-based LERCHP code can be used to predict the steady-state performance of heat pipes, including the determination of operating temperature and operating limits which might be encountered under specified conditions. The code contains a vapor flow algorithm which incorporates vapor compressibility and axially varying heat input. For the liquid flow in the wick, Darcy's formula is employed. Thermal boundary conditions and geometric structures can be defined through an interactive input interface. A variety of fluid and material options as well as a user defined one can be chosen for the working fluid, wick, and pipe materials that are suitable for different ranges of environmental and operating temperatures.

Hydrodynamic models in the LERCHP are described. We describe how appropriate thermal boundary conditions are prescribed and operating limits determined. The flowcharts of key subroutines are presented. The names of subroutines and variables are listed. An example of data input and output is presented.

In order to allow the user to judge whether the code is applicable to a particular problem, possible design choices and expected results are described in the following section.

1.1 Geometric Choices

Both straight and bent heat pipes are considered. Varying curvature may be specified along the pipe for up to twenty sections of the pipe. Cubic spline fits are used to interpolate this curvature and orientation data.

In the code, the strength of the "G" field, in which the heat pipe is operating, can be specified. Body forces may either aid or hinder the return of the liquid from the condenser to the evaporator. For operation in "G" fields, inclined straight pipe or possible bends and curvature out of the plane of the gravitational horizon, can be described to calculate variation in hydrostatic head along the pipe.

Operation of the pipe in the reflux position (evaporator lower than condenser) has not been considered.

1.2 Material Choices

Properties of the following envelope and wick materials are available in the library of the code: aluminum, beryllium, copper, Inconel, iron, molybdenum, nickel, niobium-1% zirconium, 304 stainless steel, tantalum, titanium, and tungsten.

Properties of the following working fluids are provided in the code: alkali metals (lithium, potassium, sodium, and cesium), water, ammonia, methanol, mercury, Dowtherm A, acetone, benzene, Freon-11, n-heptane, silver, toluene, and m-xylene.

There are five wick options in the code: screen, screen with arteries, sintered powder metal, sintered metal arteries, and user input.

1.3 Output of the Code

For a specific heat pipe choice, the following results can be obtained:

- Temperature distributions along the heat pipe *at* wall, wick *interfaces*, and vapor,
- *Vapor and liquid p*ressure distributions *along the pipe,*
- *Heat rejection along the condensers.*
- *The required heat input for specified temperature boundary conditions.*

The foregoing data will be provided with a warning if these limits are encountered: capillary limit and boiling limit (see Section 2.4.2). The operator can then change the input data and return the case. However, an attempt to operate within the regions excluded by the sonic or viscous limits will result in warning without data output (see Section 2.4.2). If this occurs, a suggestion to correct the situation is given.

1.4 Computational Environment

The code has been updated for use from DOS to Microsoft Windows environment. The source code was complied with Compaq Professional Visual Fortran 6.6A. The interactive text input is similar to the DOS version. The code is structured to store the calculated results (output) in a text file. *Appendix D contains an example of a case computed using the executable version of the code. This should run on machines using Microsoft Windows 7 if provision is made for suitable output to a printer or screen.*

The units used for input and output are exclusively SI. So many possibilities exist that if other choices are made, any compromise in favor of other units would be certain to inconvenience some users. The code internally employs calories in the stored thermochemical data for alkali metals to avoid possible error in converting to SI units.

2.0 Analysis

A survey of heat pipe literature revealed that many attempts were made in modeling vapor and liquid flows. Although some phenomena in heat pipes are still elusive for analysis from first principles, it is possible to develop a physically realistic steady state model. An axisymmetric compressible vapor flow model, derived by Tower and Hainley (Ref. 4), is employed in the code. This model is an extension of Busse's incompressible vapor flow model (Ref. 3).

2.1 Vapor Flow

The vapor flow in the evaporator and adiabatic sections is treated as laminar, while in the condenser, either laminar or turbulent. The ideal-gas law applies to components of the vapor of alkali metals. It is assumed that local chemical equilibrium exists among species in the vapor. In the analysis of Tower and Hainley (Ref. 4), the following assumptions were made similar to those of Busse (Ref. 3). No tangential velocity component exists at the wall, the radial pressure gradient is neglected, and the velocity components are zero at the ends of the heat pipe. In the axisymmetric model, the vapor velocity distribution and a profile factor over each cross-section, *a(z)*, is determined along the axial direction. The velocity profile is assumed as

$$v = 2v_m\left(1-\frac{r^2}{R^2}\right)\left[1+a(z)\left(\frac{r^2}{R^2}-\frac{1}{3}\right)\right] \tag{1}$$

Based on the continuity, momentum and energy conservation laws, the area-averaged pressure, p_m, area averaged temperature, T_m, and the correction factor relative to the parabolic Poiseuille velocity profile, $A(z)$, can be solved from the following three equations.

$$\left[1-\frac{4\rho_m v_m^2}{3p_m}(GB)(GRP)\right]\frac{d\ln p_m}{dz}+\left[\frac{4\rho_m v_m^2}{3p_m}(GB)(GRT)\right]\frac{d\ln T_m}{dz}+\frac{4\rho_m v_m^2}{3p_m}(HB)\frac{da}{dz}$$
$$=-\frac{8\mu v_m}{R^2 p_m}\left(1+\frac{2a}{3}\right)-\frac{8\rho_m v_m^2}{3p_m}(GB)\left[\frac{d\ln\dot{m}}{dz}-\frac{d\ln A_v}{dz}\right] \tag{2}$$

$$\left[\left(\frac{\partial h_m}{\partial\ln p_m}\right)_{T_m}-F_3 v_m^2(GRP)\right]\frac{d\ln p_m}{dz}+\left[\left(\frac{\partial h_m}{\partial\ln T_m}\right)_p+F_3 v_m^2(GRT)\right]\frac{d\ln T_m}{dz}+(HAF)\frac{da}{dz}$$
$$=8\mu\left[\frac{\left(1+2a^2/9\right)v_m}{\rho_m R^2}\right]-(HVE)\left(\frac{d\ln\dot{m}}{dz}-\frac{d\ln A_v}{dz}\right) \tag{3}$$

$$\left[1-\frac{4\rho_m v_m^2}{3p_m}(1-a/3)^2(GRP)\right]\frac{d\ln p_m}{dz}+\left[\frac{4\rho_m v_m^2}{3p_m}(1-a/3)^2(GRT)\right]\frac{d\ln T_m}{dz}-$$
$$\left[\frac{4\rho_m v_m^2}{3p}(1-a/3)\right]\frac{da}{dz}=-\frac{8\mu v_m}{R^2 p_m}(1-4a/3)-\left[\frac{4\rho_m v_m^2}{p_m}(1-a/3)^2\right]\left[\frac{d\ln\dot{m}}{dz}-\frac{d\ln A_v}{dz}\right] \tag{4}$$

where

$$GRP=1-\frac{\partial\ln R_g}{\partial\ln p},$$

$$GRT=1+\frac{\partial\ln R_g}{\partial\ln T_m},$$

$$GB = \left(1 - \frac{A}{6} + \frac{2A^2}{45}\right),$$

$$\mathrm{HB} = -\left(\frac{1}{6} - \frac{4\mathrm{A}}{45}\right),$$

$$F_3 = 8\left(\frac{1}{4} - \frac{A}{10} + \frac{A^2}{30} - \frac{2A^3}{945}\right),$$

$$HAF = -\frac{2}{5}\left(1 - \frac{2A}{3} + \frac{4A^2}{63}\right)v_m^2,$$

and

$$HVE = h_m - h_R - \frac{u_R^2}{2} + \left(\frac{3F_3 v_m^2}{2}\right).$$

The mean density, ρ_m , is determined by the ideal gas law, and the enthalpy, h_m, is a function of T_m and p_m.

The mass flux is related to the heat flux into the heat pipe by

$$\frac{dq_R}{dz} = \frac{1}{2\pi R}\frac{d\dot{m}}{dz}\left[h_{gl} + \left(\frac{1}{2\pi R}\frac{d\dot{m}}{dz}\right)^2\right] \tag{5}$$

where the kinetic energy of the injected vapor has been incorporated. Equations (2), (3), and (4) are solved with Equation (5) and other boundary conditions.

The vapor flow algorithm used in the code was first derived in Reference 4 and repeated in Reference 1. In the evaporator and adiabatic sections, the above equations are employed in the present code. For the condenser, the code has been modified as follows.

As computed by the laminar equations above, the profiles for the vapor-liquid interface temperatures T_R and the mean vapor temperature T_M in the condenser can be plotted in Figure 1.

Because of heat rejection, T_M crosses T_R at some point. If the solution using laminar Equations (1), (2), and (3) is continued in the condenser beyond this point, T_M continues to rise above T_R. Beyond the crossover point, the result certainly is spurious because it is not mathematically possible to un-mix the condensing vapor streams in the same fashion that the vapors were mixed in the evaporator. For this reason the assumption is made, whether laminar or turbulent flow is assumed in the condenser, that beyond the crossover point, T_M and T_R are equal. This couples T_M to the local vapor pressure beyond the crossover.

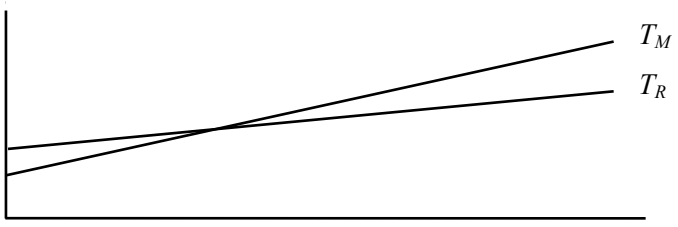


Figure 1.—The vapor-liquid interface temperature and the mean vapor temperature.

No doubt turbulence will develop in the condenser. The user is given the option of assuming laminar or turbulent flow in the condenser. Because of the possible droplet nucleation and other complications, the rate of turbulence onset is uncertain. For this reason the simplifying assumption is made that the region between the condenser entrance and the crossover point where T_M equals T_R, is the zone of transition. The portion of the condenser beyond the crossover will be regarded herein as the turbulent zone.

The phenomenon of inertial pressure recovery is considered. As the vapor stream slows in the condenser, some of the kinetic energy is recovered as pressure. An unpublished correlation by Kemme, validated by experiment and used in Reference 5, relates the pipe geometry to a factor by which the so-called inertial pressure at the condenser entrance must be multiplied to determine the pressure recovery. The inertial pressure recovery factor of Kemme is given (Ref. 5) as

$$REC = (-\mathrm{Re}_{r,c} - 2.0)/[-1.23\,\mathrm{Re}_{r,c} + (2L_e + 4L_a)/L_c] \tag{6}$$

where the condenser radial Reynolds number is defined as

$$\mathrm{Re}_{r,c} = \frac{dq_R}{dz}\frac{1}{2\pi\mu h_{gl}},$$

and the L's refer to the lengths of the evaporator, adiabatic section, and condenser, respectively. Also, q_R is the axial heat input into the vapor, and h_{gl} is the heat of evaporation.

For the region in which fully-developed turbulence is assumed, the momentum equation for flat front vapor flow with friction can be modified by Kemme's inertial pressure recovery factor *REC* to become

$$\frac{dp_m}{dz} = -(REC)\frac{d(\rho_m v_m^2)}{dz} - \frac{f\rho_m v_m^2}{R} \tag{7}$$

where f is the friction factor at axial location z, which is given as

$$f = \begin{cases} 16/\mathrm{Re}, & \mathrm{Re} < 2000; \\ 0.0791\,\mathrm{Re}^{-.25}, & 2000 < \mathrm{Re} < 20000; \\ 0.046\,\mathrm{Re}^{-.20}, & \mathrm{Re} > 20000. \end{cases} \tag{8}$$

If the flat front momentum Equation (7) above is solved for the pressure derivative using the continuity equation, the ideal-gas law and the Clausius-Clapeyron relation, the pressure derivative in the turbulent regime becomes:

$$\frac{d\ln p_m}{dz} = \frac{-REC\dfrac{\rho_m v_m^2}{p_m}\left(2\dfrac{d\ln \dot{m}}{dz} - 2\dfrac{d\ln A_g}{dz}\right) - \dfrac{FTv_m}{p_m}}{1 - REC\dfrac{\rho_m v_m^2}{p_m}\left(GRP - \dfrac{GRT}{h_{gl}}\right)}, \tag{9}$$

where

$$FT = \frac{\rho_m v_m f}{R}.$$

Here, A_g is the vapor cross section area at axial position z.

The artifice used in the present code to deal with the transition zone is as follows. The laminar flow equations developed above are used. The laminar friction factor in Equation (2) is modified as follows: A simple fairing function is defined between the condenser beginning and the station where the laminar flow equations show that T_M equals T_R:

$$turbf = 1 - 3TRM + 2TRM^2 \tag{10}$$

where

$$TRM = \frac{(T_R - T_M)}{(T_R - T_M)_0}.$$

The subscript 0 refers to the beginning of the condenser. When the laminar Equation (2) is solved, the viscous term is replaced by

$$FF = (1 - turbf)FF_l + (turbf)FT \tag{11}$$

where FF_l is the viscous term in Equation (2), i.e., the term containing μ, as shown above, with the turbulent *f*'s as shown in Equation (8) for *FT*. The viscous term in the centerline Equation (4) is summarily set to zero. At the same time, all the terms containing GRP in Equations (3) and (4), representing the inertial terms of the momentum equation, are multiplied by the Kemme pressure recovery term. When the laminar flow equations are used for the transition zone in the fashion outlined, existence and location of a crossover point for T_M and T_R are accounted for. Otherwise, the unrealistic assumption of full turbulence at the beginning of the condenser would have to be accepted.

If there are multiple condensers in series, only the last one is handled in the fashion outlined. For the previous ones, the laminar flow equations developed above are employed, and no turbulence is considered. In general, more than two condensers in series in a single pipe would seem unlikely.

The user of the code is given the option of considering the entire condenser to be laminar. In this case, Equations (2), (3), and (4) are employed up to the point of crossover of T_M and T_R. Beyond this point, only Equations (2) and (4) are used with T_M taken as the saturation pressure corresponding to the local pressure.

2.2 Liquid Flow

In a zero gravity field, the pressure drop in liquid can be described with Darcy's formula, while in a gravity field, the hydrostatic head of the liquid should also be considered. The liquid pressure is assumed equal to the vapor pressure at one point (the wet point). Commonly, for an operating steady state condition, the wet point appears at the downstream end of the condenser.

Darcy's correlation is expressed as

$$\frac{dp_l}{dz} = \frac{\mu_l \dot{m}}{\rho_l K A_w} \tag{12}$$

where the permeability, *K*, is usually empirically determined. Some correlations which can provide an approximation of the permeability are presented in Reference 12.

2.3 Thermal Boundary Conditions

Two options for thermal boundary conditions are available: (1) heat transfer rate uniform over a section and (2) specified environment temperature with heat transfer coefficients between the pipe and environment. Option 1 can handle heat conduction and heat convection with known heat transfer rate, while option 2 can handle radiation and/or convection heat transfer rate. It should be noted that option 2 should be defined for at least one section along the heat pipe. The environment temperature in this option can be viewed as a reference temperature for the physical solution.

In some applications, an experimenter may provide heat input or extraction such that the surface temperature of the evaporator or condenser will be considered fixed. For instance, in the laboratory an evaporator may be clamped within a metal block at a nearly homogeneous temperature. Option 2 can be employed for such a case by specifying the block temperature as the environment temperature, setting the radiation factor RADK as zero, and the convection coefficient HC at a very high value, for instance 100000 W/mK. This will drive the surface temperature of the pipe wall to within a small fraction of a degree K of the enclosing block. A bit of trial may be necessary to find the highest value of HC that is permitted by the code in a particular case.

2.4 Performance Limits

2.4.1 Sonic Limit

At the sonic limit the vapor flow at the end of the heat input section is choked. An approximate expression for the sonic limit derived by Busse is presented in Reference 11. This expression neglects friction effects. There are two tests for choked flow in this code. One is a sign change of the determinant of the set of equations used to find the increment in the principal dependent variables p, T_M, and A for the next step of the Runge-Kutta solution. The other is the onset of an extreme negative temperature gradient (at choke the pressure gradient, and therefore the temperature gradient, is negatively infinite). These conditions occurring before the end of the heat input or adiabatic section cause the code to take corrective action.

2.4.2 Capillary Limit

The capillary limit is defined as the maximum pressure difference between vapor and liquid that the meniscus of the vapor-liquid interface can sustain before rupture. At the point where this occurs, liquid is no longer pumped to the surface and vapor invades the wick. Dryout occurs and the pipe may overheat. The capillary limit is usually written as

$$p_g - p_l = \frac{2\sigma}{r_{eff}} \tag{13}$$

The effective pore radius governing in cases where there is a gradation of pore sizes is taken to be the largest in the pipe region in question. Some wick structures are reputed to be tolerant of meniscus failure in some pores so that local dryout does not become a problem. When a capillary limit is encountered in the code, a message is shown and execution continues. It is then up to the user to alter the pipe geometry or the operating conditions demanded, to correct the problem.

2.4.3 Entrainment Limit

Entrainment occurs when vapor shear forces lift liquid out of the wick and propel it back toward the condenser. The Weber number is customarily taken as the index of whether or not this will occur. The Weber number is defined as the ratio of inertial vapor forces attempting to dislodge the liquid to the surface tension forces restraining the liquid. One definition of the Weber number is

$$We = \frac{\rho v^2 z_c}{\sigma} \tag{14}$$

In wicked heat pipes the Weber number is related to the wick spacing. In this formulation, experimentation has shown that the critical Weber number at which the droplets dislodge is generally between 2 and 3. A default value of 2 is employed in this code. The critical dimension, z_c, is taken in this code as the effective pore size of the wicking for determining the capillary limit. When the entrainment limit is encountered in the code, a message is shown and execution continues.

2.4.4 Viscous Limit

The vapor flow in the heat pipe is driven by the pressure drop between the evaporator and the condenser. At low evaporator temperatures and low power inputs a pressure may be reached at some point in the condenser that corresponds to the vapor pressure at the ambient or environment temperature. As a result the full length of the condenser is not available for heat rejection. This condition is defined as the viscous limit. Because computation cannot continue, a message is printed, as are the data for the last completed step. In actual practice heat pipes can operate for extended periods at this condition before all the working fluid is lost to the inactive section.

2.4.5 Boiling Limit

Boiling in the wick occurs because of the temperature gradient established through the liquid in the wick when heat is being conducted. The liquid-vapor interface is saturated and the liquid at the wall is super heated. Boiling commences from nucleation sites consisting of pits or defects in the surface or the mesh openings in the wick. If the sites are sufficiently small, surface tension enables the bubbles to resist the vapor pressure within them and they remain intact. At a sufficiently high temperature gradient and heat transfer rate, bubbles grow in diameter until surface tension can no longer withstand the vapor pressure within the bubble, and bubbles detach. For determination of the boiling limit the code uses the equation presented by Marcus (1972). The default size of the critical boiling dimension in the code is 10^{-6} m. If a screen wick or a sintered wick is chosen (wick options 2, 3, 4, and 5) the critical pore size is taken to be the effective pore size for determining the capillary limit. Satisfactory information on the determination of the boiling limit is very sparse, so that a liberal factor of safety with respect to the limit must be used in all designs. If the boiling limit is encountered by operating the code, a message is provided and computation continues.

3.0 Numerical Approaches and Program Structure

The command LERCHP (or lerchp) calls Program LERCHP.EXE. (The GUI version of the code is accessed in another manner.) The flowcharts of key subroutines are presented in Appendix A. The names of all subroutines are listed and their functions are briefly explained in Appendix B. This section describes how the major subroutines interact to achieve a solution of a case which has been entered.

The main program first summons subroutine INPUT. User interactive data input is controlled by this subroutine. A user can be guided by the interface to input his/her thermal boundary conditions, geometric structures and material choices. Possible options for these inputs are illustrated in the next section. Variables are defined in Appendix C and an example case of the data input is shown in Appendix D.

When data input is completed, subroutine RUNCAS, which controls the running of the entered case, is called. RUNCAS calls subroutine GUESS. In GUESS, the heat pipe is envisioned as an isothermal bar with infinite axial conductivity. GUESS consults a tabulation containing a temperature at the approximate midpoint of the usable range of each working fluid to determine a starting temperature.

GUESS calls subroutine SUMPIP to determine the heat input to the evaporator, either specified, or computed from the boundary conditions for radiation and/or conduction from heaters. The heat rejection is similarly computed from the specified boundary conditions between the condensers and the environment. GUESS iterates until the upstream evaporator surface temperature which balances heat input and output is found. If the evaporator upstream surface temperature, T4E, so determined is less than half that provided by GUESS at the outset, a warning that the working fluid or pipe dimensions appear inappropriate is given. If T4E is more than 80 percent of the critical temperature of the working fluid, as listed in subroutine CRITIC, the same warning is given. So far, no radial wall temperature drops are considered yet.

RUNCAS then calls subroutine START, which initializes pipe wall, wick, and liquid temperatures at the upstream end of the evaporator for the first iteration throughout the pipe. The radial temperature drop between the pipe surface and the vapor-liquid interface is found by a call from START to subroutine THMRS2, which computes the thermal resistances through the pipe wall and wick to the interface.

The estimate of evaporator upstream surface temperature T4E, thus determined, is again checked by subroutine CRITIC to see that it does not exceed 80 percent of the working fluid critical temperature in which case some input condition must be changed. RUNCAS then successively calls subroutine SUMEP to iterate to a final computation of pressures and temperatures through the pipe. At the first iteration, the highest vapor Mach number at any point in the pipe is estimated. If this is less than 0.01, the incompressible vapor drop algorithm DLPINC is used. Otherwise, the compressible algorithm DLPTAD is employed. The point of transition from DLPTAD to DLPINC is smooth.

At each iteration, SUMEP calls a Runge-Kutta subroutine RUNGE (Ref. 10) to integrate the vapor pressure and temperatures through the pipe using either DLPTAD or DLPINC. During this integration, subroutine CALSPL is called to provide local boundary conditions interpolated by spline fits, and subroutine THRMS2 is called to provide the local temperatures and heat transfer through the pipe wall and wick to sources and sinks. Thermodynamic and physical properties are recomputed within THMRS2. During the computations, possible entrainment, capillary, and boiling limits are flagged, but computation proceeds.

During the stepwise integration through the pipe, a condition of choke may be identified by SUMEP in the evaporator (or adiabatic section, if present). This condition is characterized during the computation by detecting: (1) the derivative of pressure with axial distance approaching negative infinity, i.e., $dp/dZ \rightarrow -\infty$, or (2) the vapor pressure gradient dp/dZ changing sign. When either of these situations is detected, control is returned to RUNCAS for another estimate of T4E. In the case of choke within the evaporator, the remaining heat to be transferred to the fluid beyond the choke point is computed. A derivative of the Busse or Levy sonic limit equation wherein $Q \propto (P\rho)^{1/2}$, with Q the transported heat and P and ρ the upstream vapor pressure and density, provides a first estimate of a new evaporator upstream surface temperature, T4E. This moves the choke point on the next iteration toward the evaporator end. Successive increases in T4E are then made until the choke point is at the evaporator end where one dimensional flow theory permits it to occur. In the case of the adiabatic section, SUMEP is similarly called repeatedly to integrate through the pipe until the choke point is at the section downstream end. SUMEP then continues integrating to the end of the pipe or until all the available axial heat flux is exhausted, either case resulting in a normal return to RUNCAS.

After the normal return to RUNCAS, the deficit or excess of heat being transported axially at the condenser end of the pipe is noted. From this error a correction in the evaporator upstream surface temperature, T4E, is then computed by Newton-Raphson or by the secant method. SUMEP is called again and the procedure repeated until the axial heat flux at the downstream pipe end is less than 0.01 percent of the input heat.

In some cases, the vapor pressure computation in the last condenser section encounters a deficit of axial heat flux before the pipe end is reached. Accordingly, temperature T4E is dropped an appropriate amount. This lowers the condenser surface temperature, and consequently, the rejected heat. If this change in condition would result in choke being encountered before converging to thermal balance as described above, the viscous limit is deemed to have been encountered. The case is exited with a printed statement to this effect.

In another situation, choke may be indicated within the evaporator or adiabatic section, requiring an increase in temperature as described above. But this results in more heat being rejected from the pipe than has been specified as having been put in. This situation is also indicative of a viscous limit situation. An appropriate message is printed, and the case is exited.

One must note that heat pipes can operate within a viscous limit regime with the end cold. This situation is not representative of normal, desirable function for a heat pipe and can lead to freezing of working fluid in some situations. However, such a condition can exist as a transient during start up of a heat pipe.

On the other hand, if the input data of heat input, pipe dimensions, etc., are just right, the choke point may be found almost exactly at the end of an evaporator or adiabatic section while the thermal boundary conditions are met. In this case the pipe whose geometry is described by the input is truly at the “sonic limit”, and a message to this effect will be printed. This is the only instance in the code in which the “sonic limit” will be so identified.

During the iterations to achieve thermal balance, SUMEP is also computing and storing the rise in liquid pressure along the pipe required to pump the liquid. Initially, the liquid pressure at the evaporator upstream end is recorded as zero. In "G" field situations, the hydrostatic heads are also being incorporated. After convergence of the thermal iterations, the accumulated arrays of vapor and liquid pressures versus distance along the pipe are searched. The location of minimum difference between liquid and vapor is recorded as the wet point. Since in reality the liquid and vapor pressures must be nearly equal at this point, the entire record of liquid pressure versus distance is adjusted by this difference so that the pressure difference is zero at the wet point. Then the vapor-liquid pressure differences along the pipe, particularly at the upstream end, are compared to the capillary pumping capability of the wick. If the capillary limit is exceeded, a message is written to the effect “capillary limit exceeded” at the point it occurs when the output data are printed.

If the case being run results in a satisfactory solution, the user is asked whether a printout of conditions along the length of the pipe is desired. If not, only a summary is printed.

In the execution of the code as described, axial heat conduction along the pipe wall is considered negligible as compared to the heat convected in the vapor stream. This could lead to error in some pipe configurations (very thick pipe wall, small vapor passage, small heat of evaporation of the working fluid, and these factors in combination). The neglect of axial heat conduction will result in step changes in surface wall temperature when passing from one section into another. To encumber the code with a cosmetic smoothed temperature change at such points would involve adding some sort of a finite difference computation of axial wall temperature. This has not yet been done.

4.0 Input and Output of the Code

4.1 Thermal Parameters and Sections

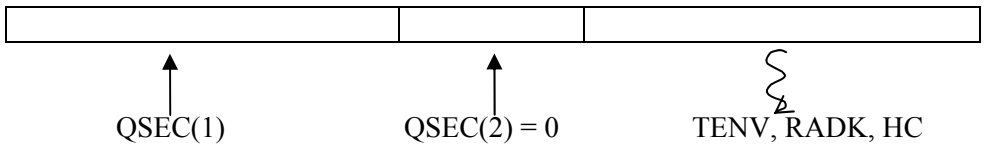
For the purpose of assigning thermal boundary conditions, the code has been designed to be flexible with respect to number and arrangement of the component parts, such as evaporator, adiabatic section and condenser. Although most heat pipes contain only an evaporator, adiabatic section and condenser, up to 20 thermal sections can be chosen as different evaporators and adiabatic section, and the last section should always be a condenser, as shown in Figure 2. The thermal section numbers are designated IS, the total number being NS.

For each section, the required thermal data can be either entered as a single value for an entire section, or input with varied values along a section at up to 20 positions, as shown in Figure 3. For the latter case, during a code execution, the data are interpolated smoothly within a section by cubic spline fits.

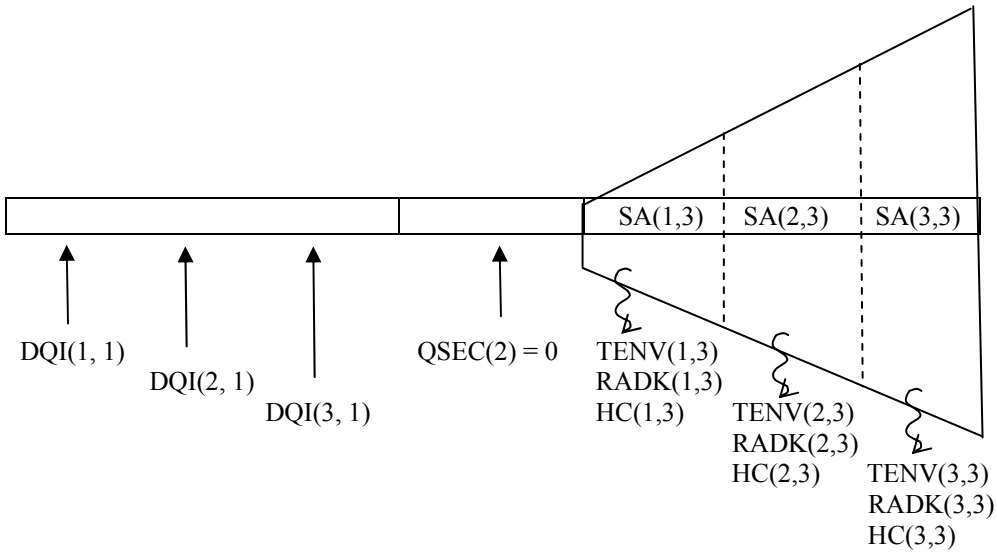
EVAP	AD	EVAP	AD	…….	AD	EV	COND

IS: 1, 2, 3, 4, …… NS-2, NS-1, NS.

Figure 2.—Thermal sections along a heat pipe.



(a) Fixed values within each section



(b) Varied values within a section

Figure 3.—Examples with thermal boundary conditions.

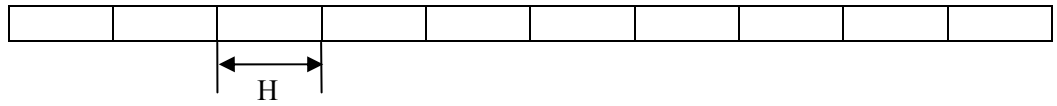
4.2 Runge Kutta Steps

The initial number of steps, ISTEP, employed in the Runge-Kutta solution may be set by the user, but the default value is 100. This choice determines the maximum step size to be adopted in the calculation. When the pressure drop between two successive steps exceeds 3 percent, the subsequent step size is subject to automatic halving during execution, as shown in Figure 4. This is particularly important when conditions change rapidly as choking is approached. Similarly if the pressure drop is less than 1 percent, the step size is doubled unless the maximum step size has been reached. In addition, when the end of a section is approached, the step size is adjusted so that a step coincides with the end of each section.

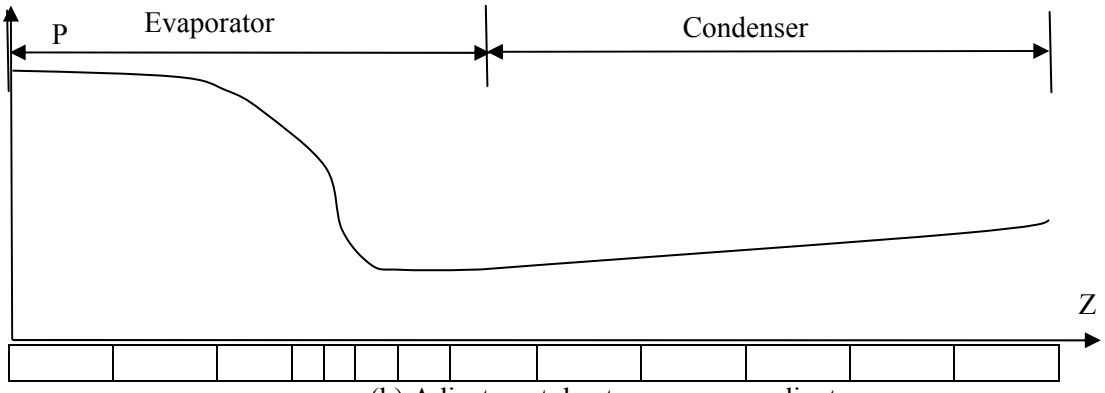
4.3 Geometric Parameters and Sections

If the pipe is in a "G" field, the user of the code establishes a reference plane of gravitational equipotential (a “horizon”). This plane is passed through the midpoint of the inside of the evaporator end cap. If the pipe is straight, the user of the code specifies only the angle with respect to the horizon. If the pipe is curved, varying curvature is specified with respect to the horizontal plane for a sequence of locations along the axis. If a few moderate bends are also present, the locations of these bends and their angles can be specified along the pipe for one to twenty sections of the pipe.

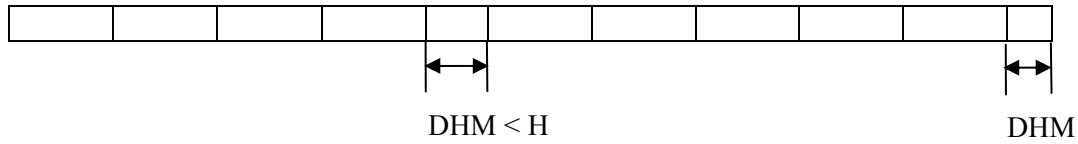
The total number of sections is designated with NSB and individual section number with ISB. These sections are similar to the familiar evaporator, adiabatic, condenser sections, *but not necessarily coincident therewith*. Bends between sections may be sharp but are required to be small since no account is made at present of liquid and vapor pressure losses due to disturbance of the flow at such points.



(a) Initial (maximum) step size



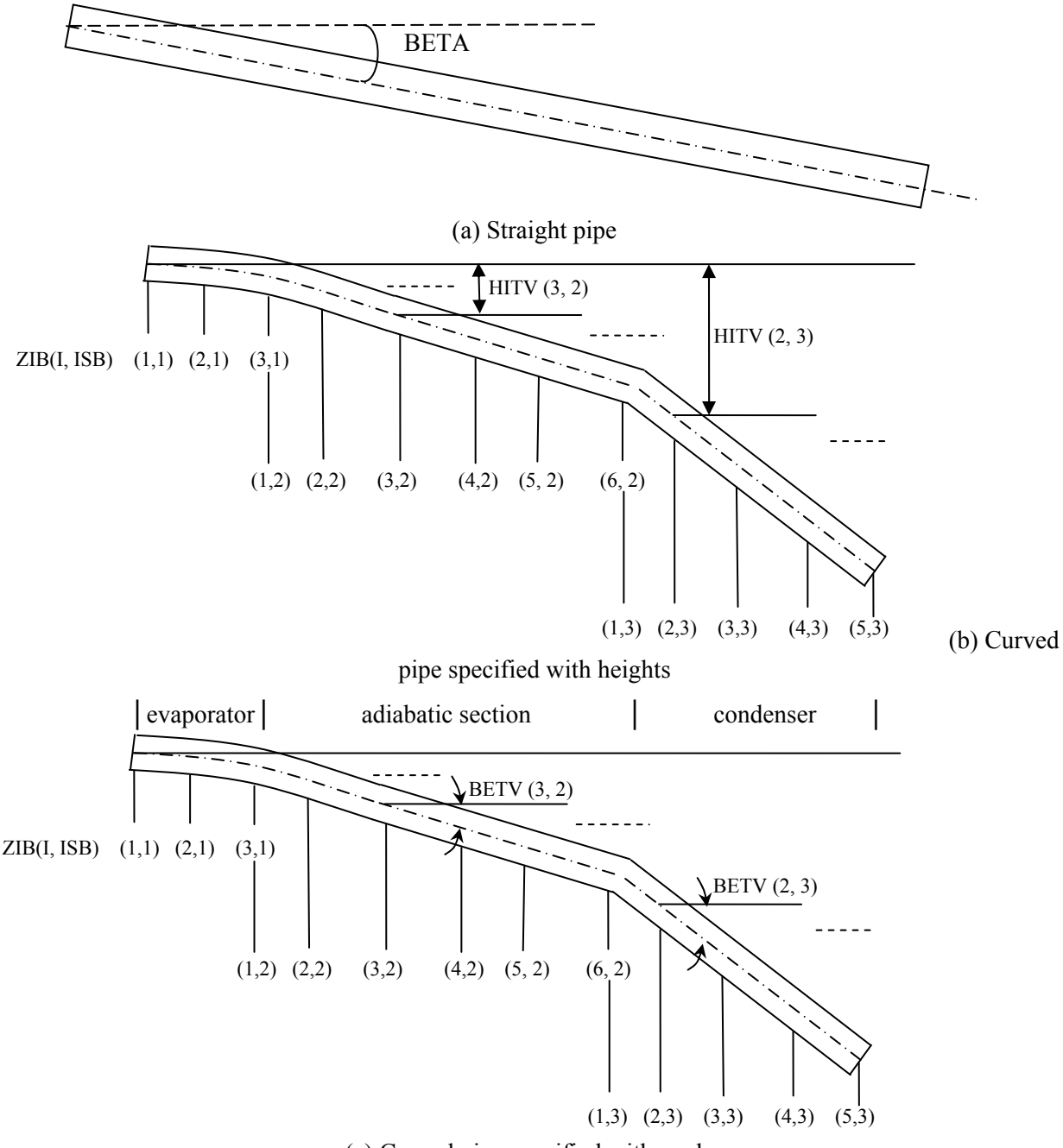
(b) Adjustment due to pressure gradients



(c) Adjustment due to mismatch of steps and section ends

Figure 4.—Runge-Kutta steps.

In the HITE option, the user specifies the vertical distance from the horizon to the pipe centerline, HITE, for a number of locations along the centerline. In this option, the angles of the pipe axis at the beginning and end of each section are required as boundary conditions for the spline fit. However, if the vertical distance is specified for more than three locations in the first or last section of the pipe, no pipe axis angles are specified for the beginning or end of the pipe. In this case, natural boundary conditions (Ref. 9) are assumed for the pipe beginning or end. Alternatively, in the BETA option the angle of the pipe with respect to the horizon, BETA, may be specified at a number of locations. All distances and angles are to be measured from the pipe centerline. In Figure 5 the pipe centerline coordinate is shown (the z coordinate of the code), and can be out of the plane of the paper.



(a) Straight pipe

(b) Curved pipe specified with heights

(c) Curved pipe specified with angles

Figure 5.—Pipe Orientation in "G" field.

The z coordinate is understood to be the actual scalar distance along the pipe axis. When the code is run, the distance from the pipe centerline to the top and bottom of the vapor space is accounted for in computing the hydraulic head at each axial or z location. The sample case provided in this report illustrates the HITE option.

4.4 Wick Structures

Five wick options are included in the code as summarized in Table 1. The wick structure of the first option is defined by the user. The wick structures of all the other four options are shown in Figure 6. References 11 and 12 discuss the parameters employed in specifying the wick options described herein.

TABLE 1.—OPTIONS OF WICK STRUCTURES

Option	Structure	
1	User defined	(1) the product of wick permeability and wick cross-sectional area, (2) the wick perimeter at the liquid-vapor interface, (3) porosity of the wick, (4) effective thermal conductivity of the liquid-filled wick, (5) axial vapor flow area, (6) effective capillary radius for pumping, (7) entrainment critical dimension, and (8) minimum nucleation radius for boiling in the liquid.
2	screen wick	(1) screen wire diameter, (2) space between screen wires, (3) crimping factor, and (4) number of screen wraps.
3	screen wicks with arteries	Information for option 2 and (1) vapor area blocked by artery, (2) artery wetted perimeter in vapor phase (3) artery inside diameter, and (4) number of arteries.
4	sintered metal wicks	(1) porosity of the wick, (2) effective radius of the wick particles, (3) experimentally determined thermal conductivity constant (Note: As discussed in Reference 11, the values are 0.34 for metal felt or fiber and 0.53 for sintered powders.), and (4) thickness of the wick.
5	sintered wicks with arteries	Information for option 4 and (1) inside diameter of the artery, (2) number of arteries, (3) vapor area blocked by artery, (4) artery wetted perimeter in vapor phase, and (5) artery inside diameter.

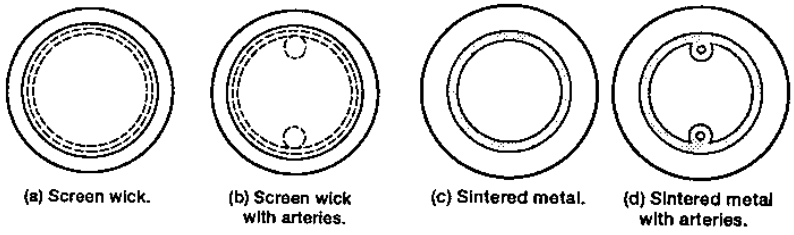


Figure 6.—Heat pipe wick structure options.

For the wick option USER INPUT the interactive queries to user are self-evident and require no further explanation. For the circular pipes as depicted in Figure 6 for screen and sintered wick options the following information will be helpful.

(a) Screen wick

If the artery option is chosen, the user enters the interior diameter of the artery or arteries, DAI, the amount of vapor area blocked by each artery, ARBLOCK, the perimeter of each artery within the vapor space, PBLOK, and the number of arteries involved.

(b) Sintered wick

For pipes with sintered wicks, the same artery information is entered. However, if the arteries are formed in the wicking in such fashion as to not protrude into the vapor space, PBLOK is not relevant and is not entered. However, the presence of the arteries within the wick structure is accounted for computing the wick properties.

To clarify the forgoing Figure 7 illustrates the area blocked by the wick, and the increase in wetted perimeter for a sintered wick with a partially imbedded artery. If the wall of the artery transports appreciable fluid, the USER INPUT option must be employed. Liquid filleting at the contact between artery and wick is neglected.

4.5 Data Output

Results at up to 100 uniformly spaced locations along the heat pipe can be saved in a file for further display. In addition, data will be stored at the beginning and end of each section whether or not it is at one of the uniformly spaced output locations. As shown in Figure 8, if an output location is between two steps of the Runge-Kutta solution, linear interpolation is employed for the output variables.

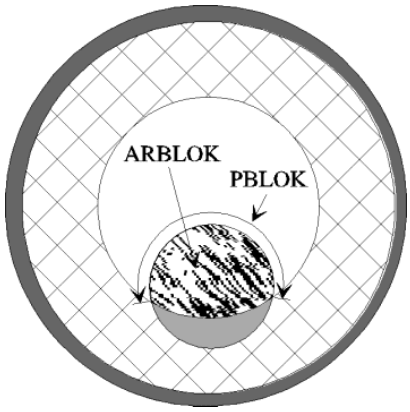


Figure 7.—A sintered wick.

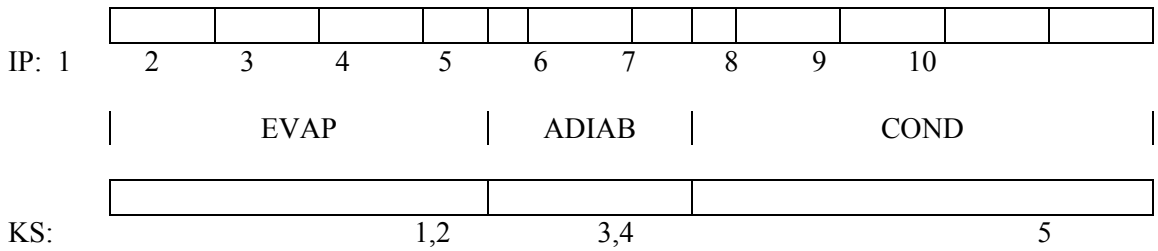


Figure 8.—An example of output locations.

Appendix A.—Flowcharts

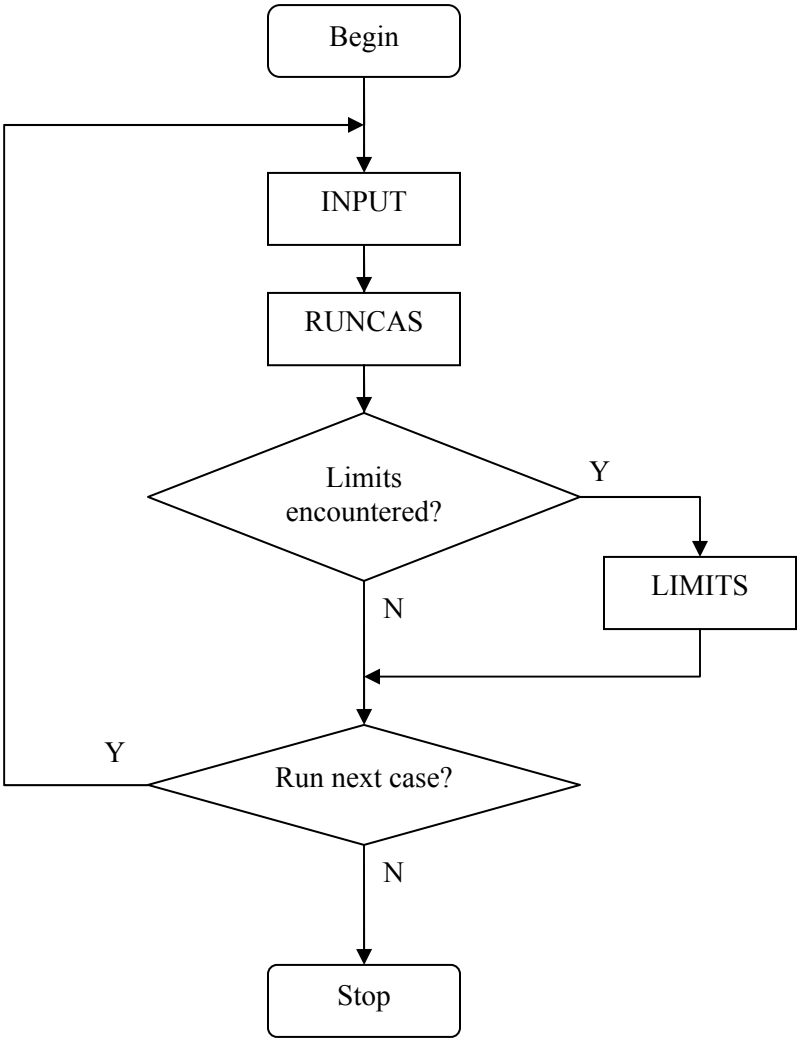


Figure 9.—Flowchart for the main program.

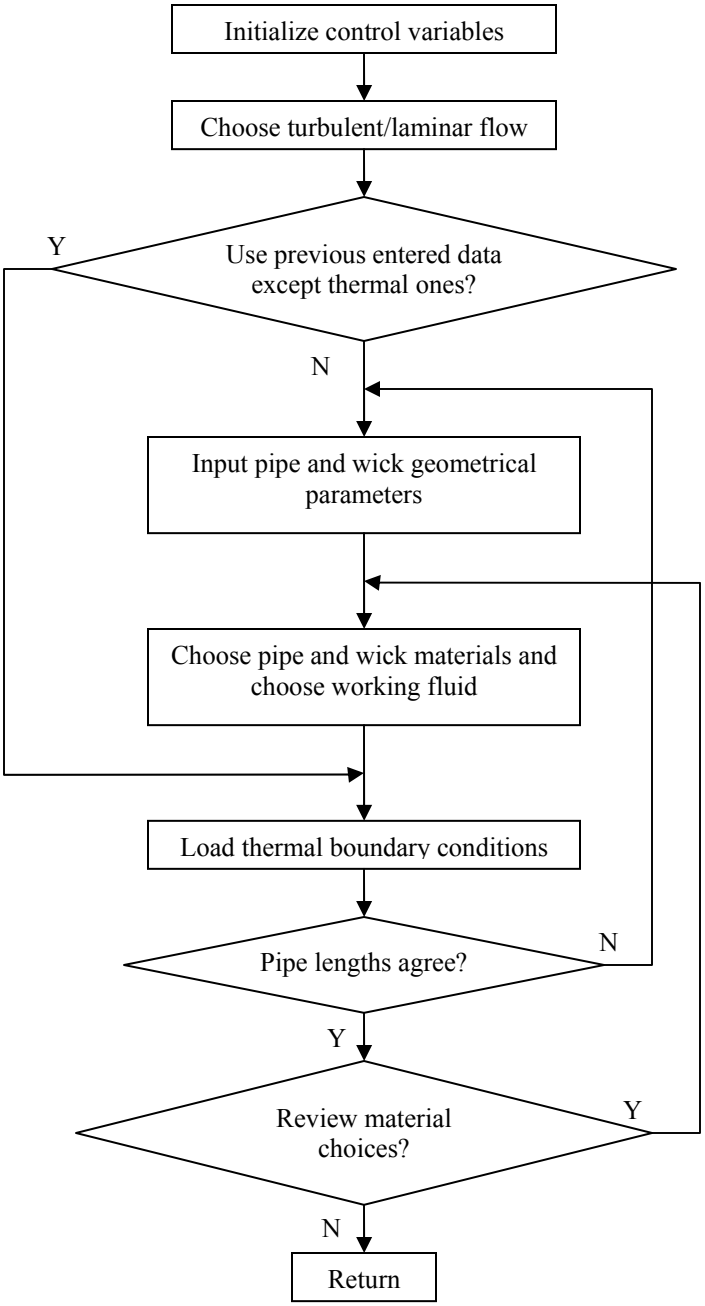


Figure 10.—Flowchart for subroutine INPUT.

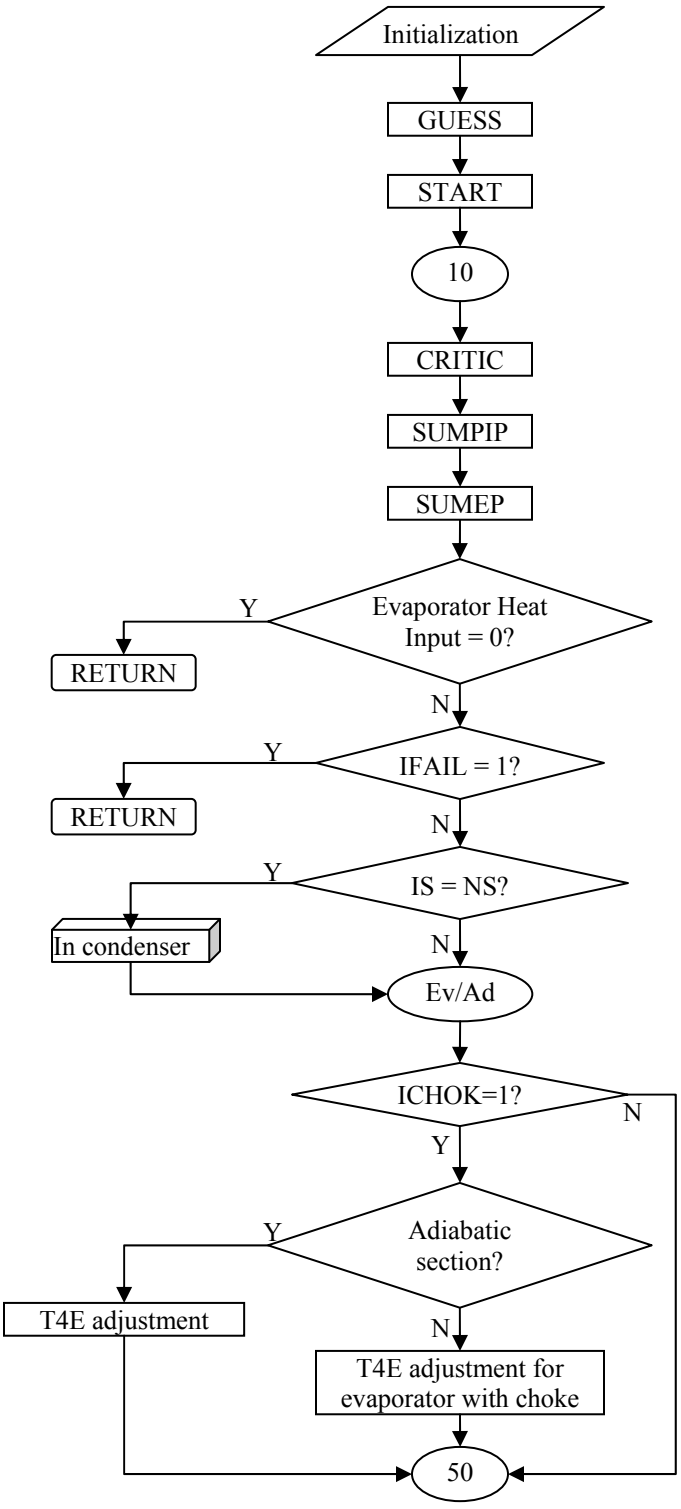


Figure 11(a).—Flowchart for subroutine RUNCAS.

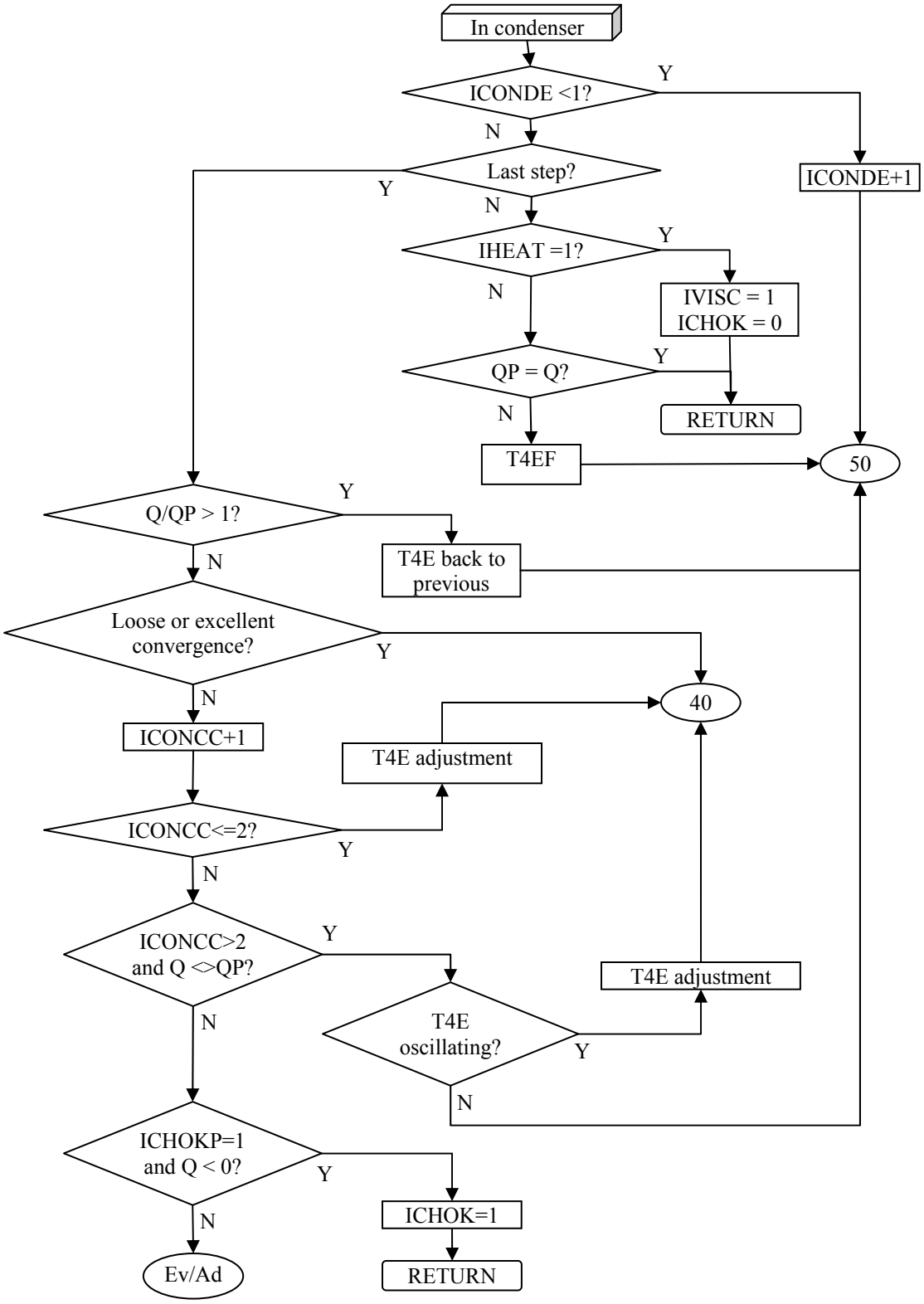


Figure 11(b).—Flowchart for subroutine RUNCAS.

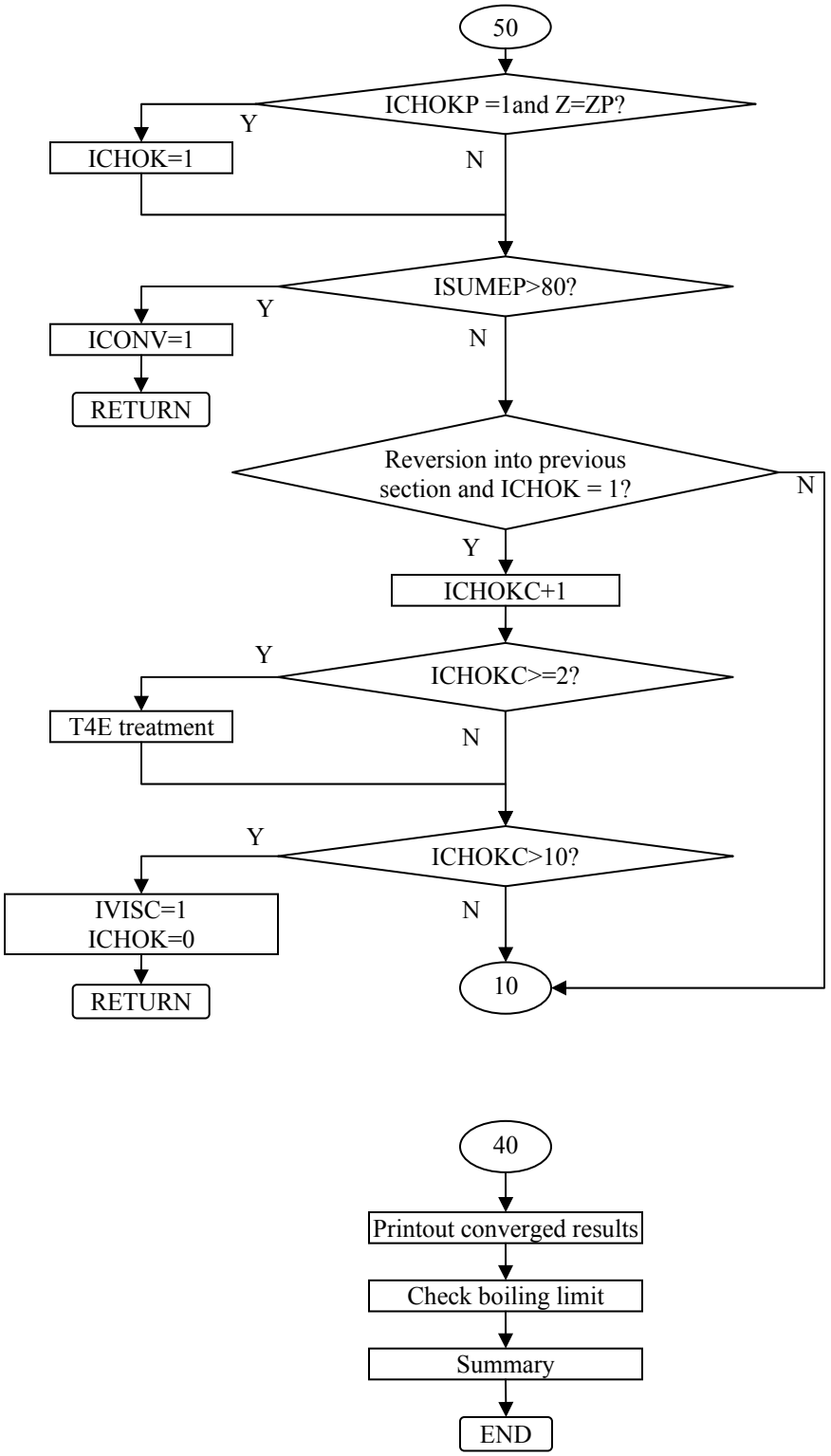


Figure 11(c).—Flowchart for subroutine RUNCAS.

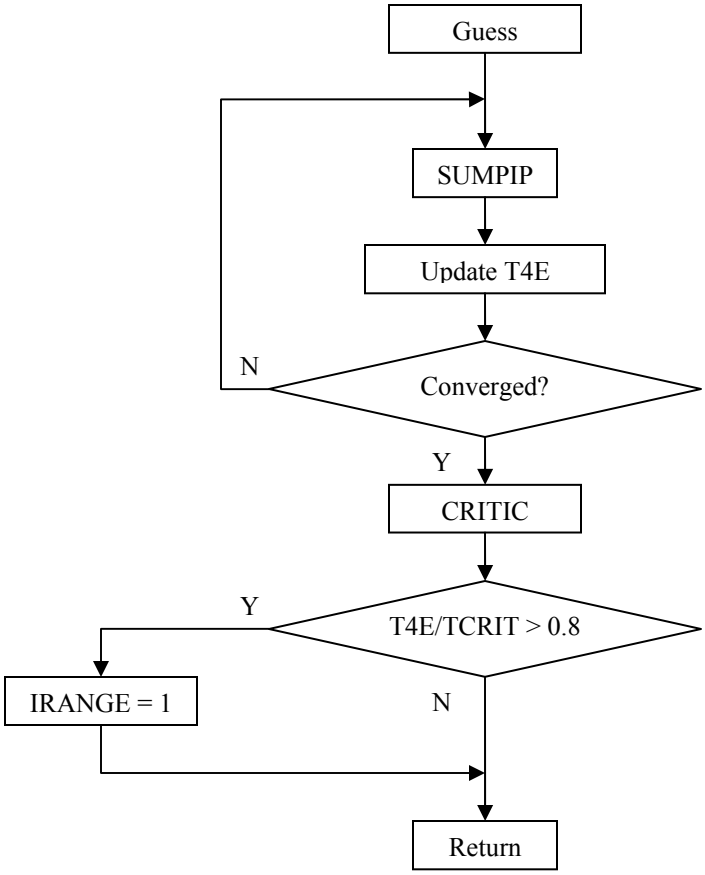


Figure 12.—Flowchart for subroutine GUESS.

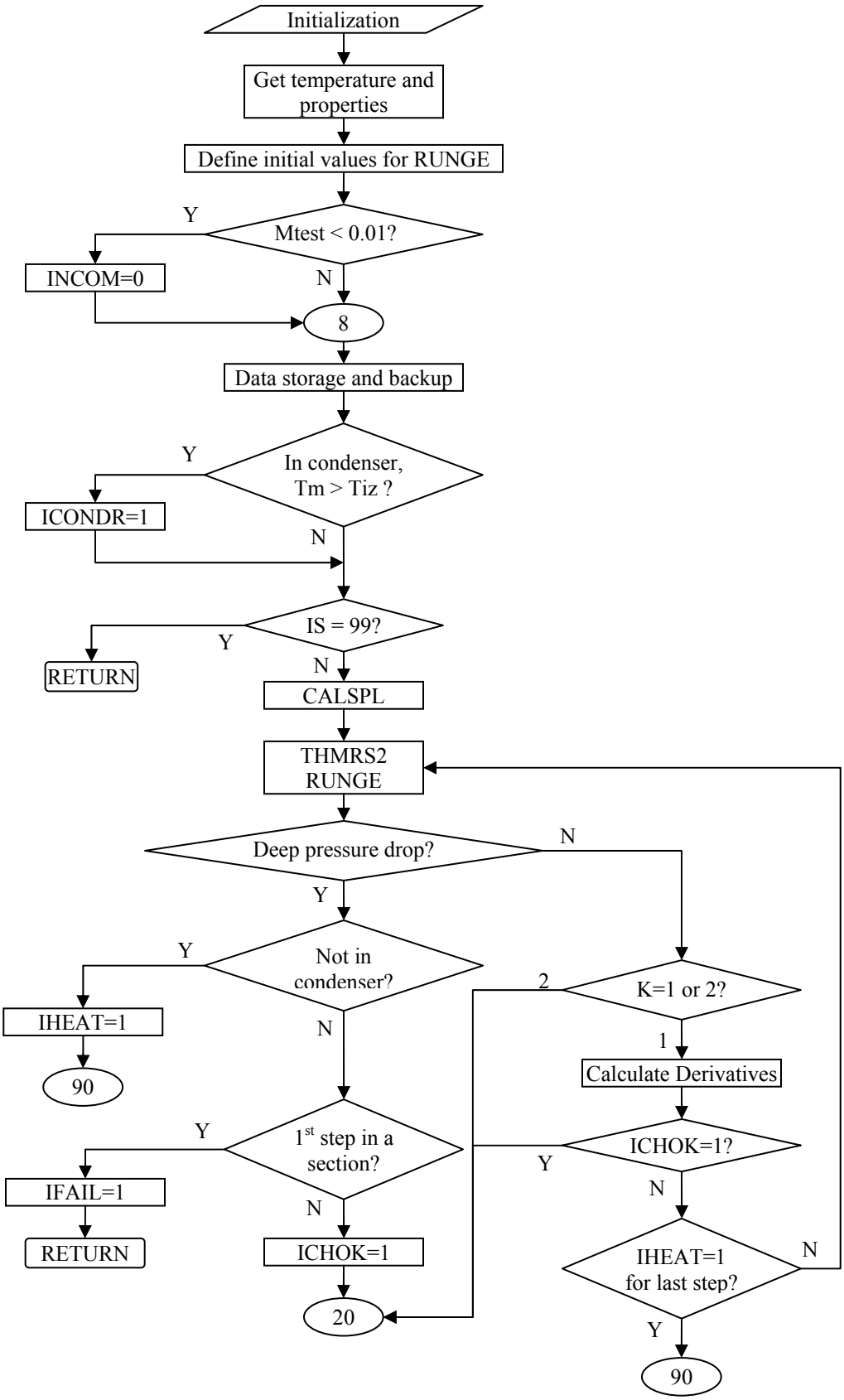


Figure 13(a).—Flowchart for subroutine SUMEP.

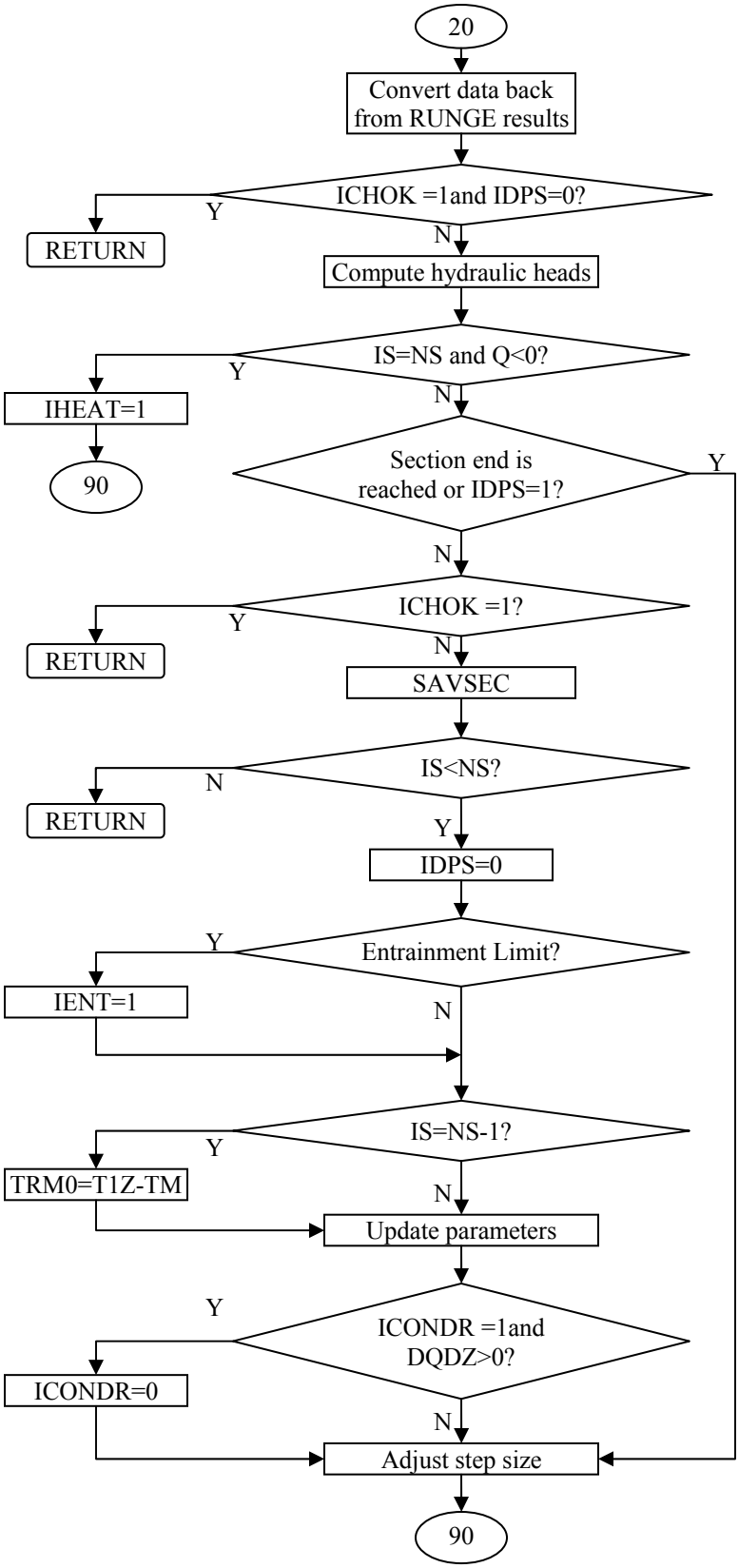


Figure 13(b).—Flowchart for subroutine SUMEP.

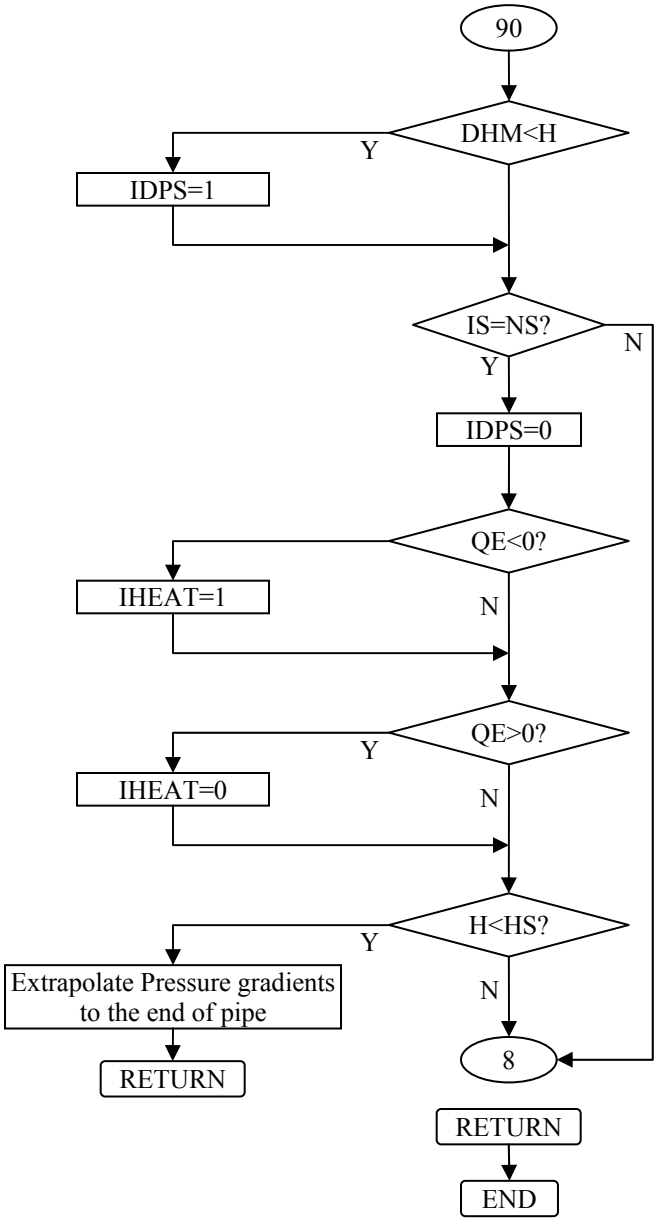


Figure 13(c).—Flowchart for subroutine SUMEP.

Appendix B.—List of Subroutines

Name	Function	Flowchart provided
ALTCA	Enter and output characters	
ALTIN	Enter and output integers	
ALTRE	Enter “real” (not complex)	
ARTMRG	Provide artery dimensions when they are not incorporated in a user defined wick entry.	
BENT	Conditions at end of sharp bend (incomplete)	
BIGBEN	Sharp bends in pipe (incomplete)	
CALSPL	Call data for SPLINS	
CAPLIM	Detects capillary limit	
COMPF	Compute K, Na, Li thermodynamic functions	
COMWIK	Completes array of wick parameters	
CRITIC	Approach of critical temperature	
BLOCK DATA FLUID	Tabulated vapor data for K, Na, Li	
DENS	Vapor densities excluding K, Na, Li	
DLPINC	Used by RUNGE at low Mach number	
DLPTAD	Used by RUNGE at high Mach number	
EQUGAS	Equilibrium vapor properties for K, Na, Li	
FINDT	Find T with given P,	
FLUPROP	Physical properties of working fluids	
FLUWRT	Print fluid name	
GASPRO	Computes gas properties	
GUESS	Guess evaporator temperature to start solution	X
HYDRO	Find wet point	
INPUTT	Choose dimensions and materials	X
KMATRL	Find pipe thermal conductivity	
LIMITS	Writes limit messages	
LODBET	Angle of pipe sections with horizon	
LODDQ	Call for thermal data input	
LODFIX	Enter section end locations	
LODSEC	Control loading of input data	
LODSEE	Enter thermal boundary conditions	
LODSEQ	Enter heat input or extraction	
LODWIK	Enter wick properties	
MATLST	List pipe materials available	
MATWRT	Show chosen materials	
PRINLI	Print output data	
PRNWIK	Show wicking chosen	
PROPTH	Find thermodynamic data of K, Na, Li	
RUNCAS	Control code execution	X
RUNGE	Execute a Runge Kutta step	
SAVSEC	Store flow variable at section end	
SPECPT	Find non-saturation vapor properties	
SPLINE	Spline fit of input data	
SPLINS	Interpolate spline fit	
SPLTOT	Spline fits for pipe orientation	
START	Initialize pipe temperature	
SUMEP	Integrate vapor condition along pipe	X
SUMPIP	Thermal balance for starting temperature	
THMRS2	Thermal resistances	
THRTB2	Provide usable data for K. Na, Li	
THRTBS	Vapor thermal data except K, Na, Li	

Appendix C.—List of Variables

A	Velocity profile parameter
AART	Artery exterior cross sectional area
AINPIP	Area of pipe interior exclusive of arteries
AIRT	Artery interior cross sectional area
AK	Product of wick area and permeability
ALM1	Distance between Z and beginning of a section
ALM2	Length of a section
AP	Blockage of vapor area by artery protrusion
AR	Factor in radiation conductance term
ARIS	Radiation conductance
AV	Vapor cross sectional area
AWICK	Area of distribution wick fixed to pipe
AWT	Thickness of artery wall
BETA	Inclination of pipe from horizontal in "g" field
BETV	Angle stored in file at specified location
C	Speed of sound
C	Temporary specific heat variable in thermal function subroutine
C11,…C33	Coefficients of vapor flow determinants
CC	Specific heat of condensed phase
CCO	Temporary variable in thermal function subroutine
CEQ	Speed of sound in equilibrium vapor containing dimers
CL(IS)	Distance between centerline to the bottom wick surface
CO	Generalized thermal property coefficient
CORR	Convergence correction factor in adiabatic section
CP	Constant pressure specific heat
CPEQ	Constant pressure specific heat in equilibrium vapor with dimers
CRIMP	Multiplying factor in wick property equations to account for crushing
DA	Artery external diameter
DAI	Artery internal diameter
DCRITE	Entrainment dimension
DEL	Pipe end deficit between input and rejected heat, i.e. total heat input (output)
DELC	Difference between vapor and liquid pressures
DELLT	Error in vapor pressure iteration
DELTCR	Theoretical critical superheat for onset of boiling
DELTL	Distance between data input station I and I+1
DELTQ	Thermal power in or out between stations I and I+1
DEN	Denominator determinant of vapor flow equations for P, T, A
DHM	Distance from station Z to end of a pipe section
DI	Interior diameter of pipe wall
DIAM	Diameter of screen wick wire

DLNAVD	Logarithm of rate of change in vapor flow area with axial distance (not currently implemented)
DLNMDZ	Logarithm of rate of change of vapor mass flow with axial distance
DMDZ	Rate of change in vapor mass flow
DO	Pipe external diameter
DQDZ	Thermal power into or out of a unit length of pipe
DQI	Thermal power into or out of a unit length of pipe at a data input point
DV	Effective diameter of the vapor space
DWBR	Entrainment dimension
DZIP	Increment in Z between two data printing points, i.e., output interval
ERR	Error in location of choking in adiabatic section
EXDEL	Error in a first estimate of pipe temperature
F(1)	Logarithm of rate of change of pressure with Z
F(2)	Logarithm of change of mean temperature with Z
F(3)	Change of velocity profile parameter A with Z
F12RT	(Gibbs free energy of dimerization)/RT
F,F1RT,	Gibbs free energy variables in thermal function
F2RT	subroutines
F3,FD,FF	Parameters in the vapor flow solution
FCO	Gibbs free energy of any species in alkali metal vapor
FCRT	(Gibbs free energy)/RT for condensed alkali metal
FG	Gravitational field strength, fraction of 1 "g"
FUN1,FUNA,FUNACL,FUNPCL,FUNT	Parameters in the vapor flow solution
G	Acceleration at earth's surface due to gravity
GB,GRT,GRP	Parameters in the vapor flow solution
H	Runge Kutta step size
H,H1,H2	Enthalpy variables in thermal function subroutines
H0	Initial choice of Runge Kutta step size
HC	Convection coefficient
HCO	Enthalpy of any species in alkali metal vapor
HCRT	(Enthalpy)/RT for condensed alkali metal
HITE	Vertical distance from axis to gravity reference plane
HITV	Height stored in file at specified location
HRT	(Enthalpy of alkali metal vapor)/RT
HVE	Parameter in the vapor flow solution
HVL	Heat of evaporation
HVLRT	(Heat of evaporation)/RT for alkali metal
IENV	0: constant over the section, 1: non-constant
IPSTEP	Data points output along pipe
ISTEP	Index of Runge-Kutta
ITCODE	non-saturation
K	Ratio of specific heats
K1,..K3	Right hand sides of vapor flow equations for P, T, A
KAPA	Wick permeability
KE	Effective wick conductivity, including liquid
KE2	Function statement for conductivity of saturated screen wick
KE4	Function statement for conductivity of saturated sintered wick
KEQ	Partial derivative of pressure with density at constant entropy for equilibrium alkali metal vapor
KF	Conductivity of liquid
KP	Conductivity of pipe
KW	Conductivity of wick material alone
LARI	Total of adiabatic lengths
LD	Boundary condition code. 1: Q in or out; 2: Q rad or/and convection
LERI	Total of evaporator lengths
LH	Length of the entire heat pipe
M1	Atomic mass of alkali metal

MACHM	Mean Mach number
MESH	Mesh spacing of screen wick in meters
MP	Pipe material code
MTEST	Approximate Mach number computed to determine whether incompressible vapor flow solution is to be used
MUL	Viscosity of liquid
MUV	Viscosity of vapor
MW	Wick material code
MWT	Molecular weight
MZ	Mass flux at axial position Z
NA	Number of arteries
NH	Number of data input points in a pipe section
NHB(ISB)	Number of locations with input data provided in ISB
NPSTEP	Number points of output along pipe
NS	Number of pipe thermal sections to be continued
NSTEP	Initial number of Runger-Kutta step chosen
NSB	Number of discrete curved or bent sections
NUM1,NUM2	Numerators of the vapor flow solutions for P, T, A
NUMWRP	Number of wraps of screen wick in the pipe
P	Vapor pressure
P1	Partial pressure of monomeric species
P2	Partial pressure of dimeric species
PARIS	Factor in variation of radiation power with pipe temperature
PC	Capillary pressure difference sustained between liquid and vapor
PE	Perimeter of vapor space in pipe
PG	Estimate of vapor pressure in an iteration
PHLNP	Partial derivative of vapor enthalpy with logarithm of pressure
PHLNT	Partial derivative of vapor enthalpy with logarithm of temperature
PHRTLP	Partial derivative of HRT with pressure logarithm
PI	3.14159
PL	Liquid pressure
PLBOT	Liquid pressure at Z on bottom of the pipe wicking
PLR0	Liquid pressure at Z referenced to evaporator end
PLRL	Factor converting PL from PLR0 to absolute value
PLRLP	Partial derivative of gas constant logarithm with pressure logarithm
PLRLT	Partial derivative of gas constant logarithm with temperature logarithm
PLTOP	Liquid pressure at Z on top of the pipe wicking
PORE	Porosity or void fraction of wicking
PQENV	Variation of total power with pipe temperature (dQ/dT = d(DEL)/dT)
Q	Axial heat transport at any axial position
QENV	Thermal power rejected to environment
QERR	Deficit of thermal power input at choke, requiring temperature increase to move choke point to evaporator end
QIN	Thermal power into the pipe
QSEC	Thermal power into or out of a pipe section
QT	Total estimated thermal power input to pipe
QTEST	Approximate Q at end of each section used to compute MTEST and DEL, i.e., the total input heat
QTI	Total estimated thermal power input to pipe from environment
R	Gas constant per mole of single species, 1.98726 cal/mole K
R12	Thermal resistance between vapor and liquid
R23	Thermal resistance through saturated wick
R34	Thermal resistance of pipe wall
R45	Thermal resistance between pipe and environment
R45R	Thermal resistance between pipe and environment due to radiation
RA	Exterior radius of artery
RADK	A radiation factor, chosen so that thermal power per unit length exchanged between pipe and environment is given by DQDZ = SIGMA*SAZ*RADKZ*(T4*T4*T4*T4 - TENV*TENV*TENV*TENV)

RADKS	Hydraulic head from pipe center to lower vapor diameter of wick
RAI	Internal radius of artery in sintered wick
RAT	Factor to interpolate data for print out
RCM	Pore radius determining minimum meniscus size
REC	Kemme pressure recovery factor
RER0	Radial Reynolds number at beginning of evaporator
RGAS	Gas constant for one kg of vapor mixture
RHO	Density of vapor
RHOL	Density of liquid
RISR	Radius of the vapor space
RM	Radius to the center of the wick
RN	Critical nucleation radius for boiling
RSS	Radius of particles in sintered wick
RTOT	Total radial thermal resistance
SA	Effective area for external heat transfer, per unit of pipe length
SBCOEF	Stefan Boltzman constant
SIGMA	Surface tension of liquid
SQM	Square of the mean Mach Number
T	Temperature
T1, T1Z, T1ZC	Temperature of vapor at the liquid interface
T2, T2Z	Temperature of liquid at the vapor interface
T3, T3Z	Temperature of pipe wall at the liquid interface
T4, T4Z, T4ZC	External temperature of the pipe wall
TBOIL	Difference T3 - T2, an index of boiling tendency
TCOR	Temperature correction for next iteration
TCRIT	Critical temperature for working fluid
TENV	Sink or environment temperature
THETA	Wetting angle of liquid on wick
TM	Mean vapor temperature
TSTIP	Test of distance from Z to end of a pipe section
TT	Temperature estimate in thermal property programs
TWALL(IS)	Wall thickness of noncircular walls
TWI	Sintered wick thickness for boiling limit calculation
TWICK	Wick thickness
UCONV	Convective conductance
UR	Radial velocity of vapor at the liquid interface
VM	Mean axial vapor velocity
WEBNUM	Weber number
WICCON	Thermal conductivity constant for sintered wick
WIDE	Space between wires of screen wick
X1	Mole fraction of monomer in vapor mixture
X2	Mole fraction of dimer in vapor mixture
XS	Length of a pipe section
Y2A, Y2Q, Y2R, Y2T, Y2U, YB2, YP1, YPN	Variables in the spline fit subroutines
Z	Axial coordinate
ZI	Axial coordinate for boundary condition input
ZIB	Axial location of pipe geometric features (bends, etc.)
ZSON	Value of *Z* at which sonic velocity is encountered
ZWEEP	Value of *Z* at which weeping of wick occurs

Note: The principal dependent variables, *p* and *T*, are modified in the code by a suffix letter which indicates a particular condition or location for which the variable is defined. For instance, while T4 is temperature on the pipe surface, T4E is a trial value or estimate updated at each iteration for a particular location at the upstream end of the evaporator. Similarly, TP indicates a value of *T* in the previous iteration, while TPP would refer to two iterations back. In general, these modifiers have the following meanings:

TABLE 2.—SUFFIX LETTER DEFINITIONS

*B	Variables pertaining to angles and heights in "g" field, replaces a vowel
*E	Estimate
*I	Indicator or Index
*IP	Value of variable at an axial position for which data will be printed out
*L	Liquid
*M	Mean
*P	Previous
*P	Printout
*R	At radial coordinate R, the vapor liquid interface
*S	Saturation, thermal section end (of pipe)
*V	Indicates that a constant parameter is redefined as variable with distance for use in spline fit
*V	Vapor
*Z	At axial position Z

Appendix D.—An Example

D.1 Data Input

The example case given here demonstrates the performance of the code. The heat pipe is made of stainless steel and has sodium as working fluid. The heat pipe has three different sections, an evaporator, an adiabatic section and a condenser. The heat pipe is heated at a constant heat flux along the evaporator, has an adiabatic section, and rejects heat to an environment at uniform temperature. The gravity field has a strength of one "G". The input procedure for the example given here is exactly as it appears on the computer screen.

```
LERCHP HEAT PIPE CODE, NASA GLENN RESEARCH CENTER
TO CONSIDER LAMINAR FLOW IN LAST CONDENSER, TYPE "Y"

TURBULENCE CONSIDERED IN LAST CONDENSER
IF THIS IS NOT THE FIRST RUN AND ALL PREVIOUSLY ENTERED DATA ARE USED EXCEPT
NEW
 THERMAL DATA, TYPE "Y"

BEGIN INPUT OF HEAT PIPE GEOMETRY
 IS THE PIPE IN A "G" FIELD? TYPE "Y"
y
 FOLLOWING INPUT IS FOR PIPES IN  "G" FIELDS
IF EVAPORATOR BELOW CONDENSER BEWARE! CODE NOT YET FOR THERMOSYPHONS.
"G" FIELD STRENGTH,MULTIPLE OF "G"      0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
      ENTER NEW VALUE
1
IS HEAT PIPE STRAIGHT? TYPE "Y"
y
STRAIGHT PIPE IN "G" FIELD.
IF EVAPORATOR ABOVE CONDENSER,PIPE ANGLE IS NEGATIVE.
PIPE CENTERLINE ANGLE, DEGREES         0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
      ENTER NEW VALUE
-3
 END HEIGHT OR ANGLE INPUT FOR PIPE IN "G" FIELD
TO CORRECT PIPE ORIENTATION INPUT, TYPE"Y"

INITIAL NUMBER OF RUNGE-KUTTA STEPS CHOSEN   100
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

LIMIT ON DATA POINTS OUTPUT ALONG PIPE IS 100.
SHOULD NOT EXCEED NUMBER OF RUNGE-KUTTA STEPS.
NUMBER OF DATA POINTS OUTPUT ALONG THE PIPE  50
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
   ENTER NEW INTEGER VALUE
20
```

```
NUMBER OF PIPE THERMAL SECTIONS TO BE CONSIDERED  2
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
   ENTER NEW INTEGER VALUE
3
ARE PIPE DIMENSIONS AND WICKING SAME IN ALL SECTIONS? TYPE "Y"
y
 IF PIPE HAS CIRCULAR WALL,TYPE"Y"
y
 CIRCULAR WALL
OUTSIDE PIPE WALL DIAMETER, DO, m   0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
      ENTER NEW VALUE
.0191
INSIDE PIPE WALL DIAMETER, DI, m    0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
      ENTER NEW VALUE
.0175
WICK TYPE CODE
 1 = USER INPUT DATA
 2 = SCREEN WICK
 3 = SCREEN WITH ARTERIES
 4 = SINTERED METAL
 5 = SINTERED METAL WITH ARTERIES
 6 = GROOVE
CHOICE OF WICK CODE           0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
   ENTER NEW INTEGER VALUE
2
DIA.SCREEN WICK WIRE, m            0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
      ENTER NEW VALUE
.5334e-4
SPACE BETWEEN WICK WIRES, m        0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
      ENTER NEW VALUE
.7366e-4
CRIMPING FACTOR                    1.0500000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

NUMBER OF SCREEN WRAPS                0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
   ENTER NEW INTEGER VALUE
2
 NUMBER OF ARTERIES, NA          0
```

```
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

CRITICAL NUCLEATION RADIUS, RN, m   0.0000000
DEFAULT VALUE = 1.0E-6
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

TO REVIEW OR CORRECT THE DIAMETER AND WICK INPUT,TYPE "Y"

ALL WICKING,X-SECTION DIMENSIONS SAME AS THERMAL SECTION 1
MATERIAL CHOICE CODE
   1 = STAINLESS STEEL 304
   2 = TITANIUM
   3 = IRON
   4 = NICKEL
   5 = ALUMINUM
   6 = COPPER
   7 = NIOBIUM-1%ZIRCONIUM
   8 = TUNGSTEN
   9 = INCONEL
  10 = MOLYBDENUM
  11 = TANTALUM
  12 = BERYLLIUM
TYPE OF PIPE MATERIAL                  0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
   ENTER NEW INTEGER VALUE
1
 TYPE OF WICK MATERIAL                 0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
   ENTER NEW INTEGER VALUE
1
 FLUID TYPE CODE                       0
  1 = LITHIUM
  2 = POTASSIUM
  3 = SODIUM
  4 = WATER
  5 = AMMONIA
  6 = METHANOL
  7 = MERCURY
  8 = DOWTHERM A
  9 = ACETONE
 10 = BENZENE
 11 = CESIUM, NO DIMERS CONSIDERED
 12 = FREON-11
 13 = N-HEPTANE
 14 = SILVER
 15 = TOLUENE
 16 = M-XYLENE
 FLUID TYPE                            0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
```

```
y
  ENTER NEW INTEGER VALUE
3
 WETTING ANGLE, DEG                    0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

 WEBER CONSTANT,DEFAULT 2*PI,SEE INSTRUCTIONS   6.2831802
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

AVAILABLE CHOICES OF THERMAL CONDITIONS FOR SECTIONS
 1   HEAT INPUT OR OUTPUT SPECIFIED IN SECTION
 2   ENVIRONMENT OR HEATER TEMPERATURE GIVEN IN SECTION
 CHOICE FOR SECTION # 1------>0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
  ENTER NEW INTEGER VALUE
1
HEAT IN OR OUT ALONG SECTION IS CONSTANT
 IF CHANGE,TYPE "Y"

 AXIAL LOCATION OF PIPE BEGINNING, m         0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

 AXIAL LOCATION OF SECTION END, m            0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
     ENTER NEW VALUE
.2
HEAT INTO OR OUT OF SECTION,WATTS           0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
     ENTER NEW VALUE
500
AVAILABLE CHOICES OF THERMAL CONDITIONS FOR SECTIONS
 1   HEAT INPUT OR OUTPUT SPECIFIED IN SECTION
 2   ENVIRONMENT OR HEATER TEMPERATURE GIVEN IN SECTION
 CHOICE FOR SECTION # 2------>0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
  ENTER NEW INTEGER VALUE
1
HEAT IN OR OUT ALONG SECTION IS CONSTANT
 IF CHANGE,TYPE "Y"

 AXIAL LOCATION OF SECTION END, m            0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
     ENTER NEW VALUE
.4
HEAT INTO OR OUT OF SECTION,WATTS           0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
```

```
AVAILABLE CHOICES OF THERMAL CONDITIONS FOR SECTIONS
 1    HEAT INPUT OR OUTPUT SPECIFIED IN SECTION
 2    ENVIRONMENT OR HEATER TEMPERATURE GIVEN IN SECTION
 CHOICE FOR SECTION # 3------>0
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
   ENTER NEW INTEGER VALUE
2
DIMENSIONS,PROPERTIES IN SECTION ARE CONSTANT
 IF CHANGE,TYPE "Y"

 AXIAL LOCATION OF SECTION END, m            0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
     ENTER NEW VALUE
.6
ENVIRONMENT OR HEATER TEMPERATURE, TENV, K    0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
     ENTER NEW VALUE
273
SPECIFIC AREA PER UNIT LENGTH, SA   0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
     ENTER NEW VALUE
.15
RADIATION FACTOR RADK              0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER
y
     ENTER NEW VALUE
.8
 CONVECTION COEFFICIENT HC, W/m**2 K   0.0000000
 IF CHANGE, TYPE "Y", THEN PRESS ENTER

IF SHARP BENDS CAUSING PRESSURE DROP,TYPE "Y" OR "y"

 TO REVIEW OR CORRECT MATERIALS, FLUIDS, THERMAL CONDITIONS, TYPE "Y"
```

D.2 Data Output

D.2.1 Display during Computing

The output data for the example with input given in D.1 are presented here exactly as they appear by running the code.

```
COMPUTING-------->
THERMAL CONVERGENCE EXCELLENT,Q/QIN<.0001
DO YOU WISH TO OMIT PRINTOUT OF DATA ALONG THE PIPE? TYPE  Y

 MENISCUS PRESS. DIFFERENCE
   P - PLTOP, N/m**2        =        22482.922
 CAPILLARY LIMIT  PC, N/m**2 =        7989.6851
 CAPILLARY LIMIT EXCEEDED
 MENISCUS PRESS. DIFFERENCE
   P - PLTOP, N/m**2        =        16998.570
 CAPILLARY LIMIT  PC, N/m**2 =        8035.6338
 CAPILLARY LIMIT EXCEEDED
 MENISCUS PRESS. DIFFERENCE
   P - PLTOP, N/m**2        =        5886.6475
 CAPILLARY LIMIT  PC, N/m**2 =        8077.3003

SUMMARY
THERMAL CONVERGENCE FOUND. RESULT MAY NOT BE VALIDCHECK LIMITS.
 EVAPORATOR UPSTREAM SURFACE TEMP, K   803.32965
 EVAPORATOR UPSTREAM VAPOR TEMP, K     800.76868
 CONDENSER DOWNSTREAM SURFACE TEMP,K   779.09937
 CONDENSER DOWNSTREAM VAPOR TEMP, K    781.94031
 TOTAL HEAT INPUT TO PIPE, WATTS       499.99973
 MAXIMUM MEAN MACH NUMBER IN PIPE     0.36962253
 WET POINT IS LOCATED AT Z =          0.60000002
 MAXIMUM MENISCUS PRESS.DIFFERENCE
   P - PLTOP, n/m**2 =                22482.922
 CAPILLARY LIMIT  PC,N/m**2           7989.6851
 SEE "README" FOR DESCRIPTION OF FOLLOWING:
 "SONIC LIMIT" DURING ITERATION WAS
   NOT IDENTIFIED BEFORE THERMAL BALANCE SOUGHT IN CONDENSER.
 CAPILLARY LIMIT EXCEEDED.ARTERIES, OR FINER SCREEN AND PORES REQUIRED AT
THIS C
ONDITION
CASE FINISHED. BEGIN NEW ONE
 DO YOU WISH TO QUIT? TYPE "Y"
y
 ARE YOU SURE?
y
```

D.2.2 Saved Results

The saved results for the example with input given in D 1 are given as follows.

```
LERCHP HEAT PIPE CODE, NASA GLENN RESEARCH CENTER
TURBULENCE CONSIDERED IN LAST CONDENSER
BEGIN LISTING OF INPUT DATA
y
"G" FIELD STRENGTH,FRACTIONS OF "G"        1.0000000
 STRAIGHT PIPE AT ANGLE, DEG. (NEGATIVE IS EVAPORATOR HIGHER)  -3.0000000
INITIAL # OF RUNGE-KUTTA STEPS CHOSEN   100
NUMBER OF DATA POINTS OUTPUT ALONG PIPE 20
NUMBER OF THERMAL SECTIONS IN THE PIPE    3
 IF PIPE HAS CIRCULAR WALL,TYPE"Y"
 CIRCULAR WALL
SCREEN WICK
WIRE DIAMETER, m                 0.53340002E-04
SPACE BETWEEN WICK WIRES, m        0.73659998E-04
CRIMPING FACTOR                   1.0500000
NUMBER OF SCREEN WRAPS               2
ALL WICKING,X-SECTION DIMENSIONS SAME AS THERMAL SECTION 1
THERMAL SECTION NUMBER  1
 SCREEN WICK SUBROUTINE
 DO=  0.19099999E-01 DI=  0.17500000E-01 TWI=     0.21336001E-03
 AK=  0.62904002E-15 PE=  0.53637244E-01 PORE=    0.65363967
 AV=  0.22894092E-03 RCM=  0.36829999E-04
 DWBR=  0.73659998E-04 RSS=  0.0000000     RN=  0.10000000E-05      NA= 0
TYPE OF PIPE MATERIAL CHOSEN
   1 = STAINLESS STEEL 304
 TYPE OF WICK MATERIAL CHOSEN
   1 = STAINLESS STEEL 304
 WEBER NUMBER                     6.2831802
 WETTING ANGLE, DEG                0.0000000
 WORKING FLUID
   SODIUM
SECTION NUMBER  1  HEAT INPUT SPECIFIED IN THIS SECTION
I=1 ZI=   0.0000000    I=2 ZI=  0.20000000    QSEC=   500.00000
SECTION NUMBER  2  HEAT INPUT SPECIFIED IN THIS SECTION
I=1 ZI=  0.20000000    I=2 ZI=  0.40000001    QSEC=   0.0000000
SECTION NUMBER  3  ENVIRONMENT OR HEATER TEMPERATURE SPECIFIED IN THIS
SECTION
 ZI(1)  0.40000001     ZI(2)  0.60000002
   SA= 0.15000001     RADK= 0.80000001    HC=  0.0000000    TENV=  273.00000
THERMAL CONVERGENCE EXCELLENT,Q/QIN<.0001


BEGIN PRINTOUT OF RESULTS
 MENISCUS PRESS. DIFFERENCE
   P - PLTOP, N/m**2         =         22482.922
 CAPILLARY LIMIT  PC, N/m**2 =         7989.6851
 CAPILLARY LIMIT EXCEEDED
```

```
BEGIN SECTION # 1
Z=      0.0000000
 P=     938.11243     PLBOT=  -21406.676     PLTOP=  -21544.809
 T1Z=    800.76868     T4Z=     803.32965     TM=      800.76868
 VM=     0.0000000     MACHM=   0.0000000     A=       0.36690533
 DQDZ=   2500.0000     Q=       0.0000000     HITE=    0.0000000

Z=     0.30000001E-01
 P=     935.46832     PLBOT=  -21292.490     PLTOP=  -21430.631
 T1Z=    800.62122     T4Z=     803.18219     TM=      800.55756
 VM=     22.832644     MACHM=  0.39655376E-01 A=       0.36883152
 DQDZ=   2500.0000     Q=       75.000000     HITE=  -0.15700775E-02

Z=     0.60000002E-01
 P=     926.57172     PLBOT=  -20941.402     PLTOP=  -21079.562
 T1Z=    800.12268     T4Z=     802.68365     TM=      799.82953
 VM=     46.055965     MACHM=  0.80037639E-01 A=       0.37491730
 DQDZ=   2500.0000     Q=       150.00002     HITE=  -0.31401548E-02

Z=     0.90000004E-01
 P=     911.01727     PLBOT=  -20348.062     PLTOP=  -20486.258
 T1Z=    799.24103     T4Z=     801.80200     TM=      798.53619
 VM=     70.133522     MACHM=  0.12201223     A=       0.38549078
 DQDZ=   2500.0000     Q=       225.00002     HITE=  -0.47102333E-02

Z=     0.12000000
 P=     888.26605     PLBOT=  -19511.521     PLTOP=  -19649.768
 T1Z=    797.92767     T4Z=     800.48865     TM=      796.59509
 VM=     95.638802     MACHM=  0.16665655     A=       0.40122277
 DQDZ=   2500.0000     Q=       300.00012     HITE=  -0.65943287E-02

Z=     0.15000001
 P=     857.41943     PLBOT=  -18430.285     PLTOP=  -18568.604
 T1Z=    796.09943     T4Z=     798.66040     TM=      793.86560
 VM=     123.35936     MACHM=  0.21546248     A=       0.42325315
 DQDZ=   2500.0000     Q=       375.00000     HITE=  -0.78503918E-02

Z=     0.18000001
 P=     816.98517     PLBOT=  -17102.070     PLTOP=  -17240.488
 T1Z=    793.61438     T4Z=     796.17535     TM=      790.10199
 VM=     154.50066     MACHM=  0.27073732     A=       0.45354337
 DQDZ=   2500.0000     Q=       449.99985     HITE=  -0.94204713E-02

Z=     0.20000000
 P=     783.44214     PLBOT=  -16076.625     PLTOP=  -16215.129
 T1Z=    791.47040     T4Z=     794.03137     TM=      786.80066
 VM=     178.13921     MACHM=  0.31307250     A=       0.47998706
 DQDZ=   2500.0000     Q=       499.99973     HITE=  -0.10467185E-01
 MENISCUS PRESS. DIFFERENCE
   P - PLTOP, N/m**2        =         16998.570
 CAPILLARY LIMIT  PC, N/m**2 =         8035.6338
```

CAPILLARY LIMIT EXCEEDED

Z= 0.20000000
P= 783.44226 PLBOT= -16076.625 PLTOP= -16215.129
T1Z= 791.47040 T4Z= 791.47040 TM= 786.80066
VM= 178.13921 MACHM= 0.31307250 A= 0.47998706
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.10467185E-01

Z= 0.21000001
P= 777.41864 PLBOT= -15528.207 PLTOP= -15666.727
T1Z= 791.07697 T4Z= 791.07697 TM= 786.57336
VM= 179.51469 MACHM= 0.31547824 A= 0.45526853
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.11304548E-01

Z= 0.24000001
P= 759.55316 PLBOT= -13882.189 PLTOP= -14020.756
T1Z= 789.89423 T4Z= 789.89423 TM= 785.91541
VM= 183.73235 MACHM= 0.32284200 A= 0.39507690
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.12874627E-01

Z= 0.27000001
P= 741.85022 PLBOT= -12235.059 PLTOP= -12373.672
T1Z= 788.69812 T4Z= 788.69812 TM= 785.28644
VM= 188.12634 MACHM= 0.33049437 A= 0.35163769
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.14444707E-01

Z= 0.30000001
P= 724.12396 PLBOT= -10586.852 PLTOP= -10725.514
T1Z= 787.47534 T4Z= 787.47534 TM= 784.67029
VM= 192.75211 MACHM= 0.33853501 A= 0.32066247
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.16014786E-01

Z= 0.33000001
P= 706.21246 PLBOT= -8937.5771 PLTOP= -9076.2900
T1Z= 786.21295 T4Z= 786.21295 TM= 784.05243
VM= 197.66934 MACHM= 0.34707063 A= 0.29922697
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.17584866E-01

Z= 0.36000001
P= 687.96582 PLBOT= -7287.2109 PLTOP= -7425.9766
T1Z= 784.89801 T4Z= 784.89801 TM= 783.41675
VM= 202.94476 MACHM= 0.35622102 A= 0.28529385
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.19154945E-01

Z= 0.39000002
P= 669.23987 PLBOT= -5635.7061 PLTOP= -5774.5264
T1Z= 783.51654 T4Z= 783.51654 TM= 782.74615
VM= 208.65581 MACHM= 0.36612540 A= 0.27743530
DQDZ= 0.0000000 Q= 499.99973 HITE= -0.20725025E-01
Z= 0.40000001
P= 662.86609 PLBOT= -5084.9414 PLTOP= -5223.7812

```
 T1Z=    783.03864     T4Z=     783.03864     TM=      782.51178
 VM=     210.67200     MACHM=  0.36962253     A=      0.27598944
 DQDZ=   0.0000000     Q=       499.99973     HITE=  -0.20934397E-01
 MENISCUS PRESS. DIFFERENCE
  P - PLTOP, N/m**2        =         5886.6475
 CAPILLARY LIMIT  PC, N/m**2 =         8077.3003

Z=     0.40000001
 P=      662.86627     PLBOT=  -5084.9414     PLTOP=  -5223.7812
 T1Z=    783.03864     T4Z=     780.18030     TM=      782.51178
 VM=     210.67200     MACHM=  0.36962253     A=       *********
 DQDZ=  -2509.3179     Q=       499.99973     HITE=  -0.20934397E-01

Z=     0.42000002
 P=      659.82178     PLBOT=  -4023.0508     PLTOP=  -4161.9004
 T1Z=    782.80896     T4Z=     779.95367     TM=      782.80896
 VM=     190.67711     MACHM=  0.33426175     A=       *********
 DQDZ=  -2506.5886     Q=       449.84113     HITE=  -0.22190461E-01

Z=     0.45000002
 P=      656.39667     PLBOT=  -2632.8145     PLTOP=  -2771.6738
 T1Z=    782.54944     T4Z=     779.69806     TM=      782.54944
 VM=     159.76529     MACHM=  0.28010911     A=       *********
 DQDZ=  -2503.2175     Q=       374.69531     HITE=  -0.23760540E-01

Z=     0.48000002
 P=      653.58325     PLBOT=  -1487.4688     PLTOP=  -1626.3359
 T1Z=    782.33539     T4Z=     779.48712     TM=      782.33539
 VM=     128.47330     MACHM=  0.22527055     A=       *********
 DQDZ=  -2500.4321     Q=       299.64188     HITE=  -0.25330620E-01

Z=     0.50999999
 P=      651.37946     PLBOT=  -586.89258     PLTOP=  -725.76758
 T1Z=    782.16718     T4Z=     779.32141     TM=      782.16718
 VM=     96.872337     MACHM=  0.16987449     A=       *********
 DQDZ=  -2498.2373     Q=       224.66350     HITE=  -0.26900699E-01

Z=     0.53999996
 P=      649.78333     PLBOT=   69.015625     PLTOP=  -69.863281
 T1Z=    782.04498     T4Z=     779.20111     TM=      782.04498
 VM=     65.036018     MACHM=  0.11405360     A=       *********
 DQDZ=  -2496.6340     Q=       149.74258     HITE=  -0.28470779E-01

Z=     0.56999993
 P=      648.79486     PLBOT=   480.34180     PLTOP=   341.45898
 T1Z=    781.96924     T4Z=     779.12646     TM=      781.96924
 VM=     33.039257     MACHM=  0.57943113E-01 A=       *********
 DQDZ=  -2495.6255     Q=       74.860863     HITE=  -0.30040858E-01

Z=     0.60000002
 P=      648.42749     PLBOT=   648.42773     PLTOP=   509.54492
```

```
 T1Z=    781.94031     T4Z=     779.09937     TM=      781.94171
 VM=     *********     MACHM=   *********     A=       *********
 DQDZ=  -2495.2441     Q=       7.4856515     HITE=  -0.31401549E-01
TBOIL(1)  0.20762403    DELTCR   15130.102
TBOIL IS GRADIENT ACROSS LIQUID, DELTCR IS THEORETICAL GRADIENT NEEDED TO
BOIL

SUMMARY
 THERMAL CONVERGENCE FOUND. RESULT MAY NOT BE VALID, CHECK LIMITS.
 EVAPORATOR UPSTREAM SURFACE TEMP, K   803.32965
 EVAPORATOR UPSTREAM VAPOR TEMP, K     800.76868
 CONDENSER DOWNSTREAM SURFACE TEMP,K   779.09937
 CONDENSER DOWNSTREAM VAPOR TEMP, K    781.94031
 TOTAL HEAT INPUT TO PIPE, WATTS       499.99973
 MAXIMUM MEAN MACH NUMBER IN PIPE     0.36962253
 WET POINT IS LOCATED AT Z =          0.60000002
 MAXIMUM MENISCUS PRESS.DIFFERENCE
  P - PLTOP, n/m**2 =                 22482.922
 CAPILLARY LIMIT  PC,N/m**2           7989.6851
 SEE "README" FOR DESCRIPTION OF FOLLOWING:
 "SONIC LIMIT" DURING ITERATION WAS
  NOT IDENTIFIED BEFORE THERMAL BALANCE SOUGHT IN CONDENSER.
 CAPILLARY LIMIT EXCEEDED.ARTERIES, OR FINER SCREEN AND PORES REQUIRED AT
THIS CONDITION
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References

1. Tower, L.K., NASA Lewis Steady-State Heat Pipe Code Users Manual Version 2, DOS INPUT, NASA TM 209807, 2000.
2. Tower, L.K., Baker, K.W.; and Marks, T.S., NASA Lewis Steady-State Heat Pipe Code Users Manual, NASA TM 105161, 1992.
3. Busse, C.A., Pressure Drop in the Vapor Phase of Long Heat Pipes, IEEE Conference Record of the Thermionic Conversion Specialist Conference, pp. 391-398, 1967.
4. Tower, L.K. and Hainley, D.C., An Improved Algorithm for the Modeling of Vapor Flow in Heat Pipes, NASA CR-185179, 1989.
5. Woloshun, K., Merrigan, M.A. and Best, E.D., HTPIPE: A Steady State Heat Pipe Analysis Program, A User's Manual. LA-11324-M, UC-405, 1988.
6. DeMichele, D.W., *The Numerical Solution to Axial Symmetric Compressible Flow With Mass Injection and Its Application to Heat Pipes*, Ph.D. Thesis, University of Arizona, 1970.
7. Busse, C.A., Theory of Ultimate Heat Transfer Limit of Cylindrical Heat Pipes, Inst. J. Heat and Mass Transfer, Vol. 16, pp.169-186, 1973.
8. Levy, E.K., Effects of Friction on the Sonic Velocity Limit in Sodium Heat Pipes, ASME Paper HPT-71-022.
9. Press, W.H., et al., *Numerical Recipes: The Art of Scientific Computin*g, Cambridge University Press, Cambridge, 1986.
10. White, F.M., *Viscous Fluid Flow,* McGraw-Hill, 1974.
11. Dunn, P.; and Reay, D.A.: *Heat Pipes*. Third Ed., Pergamon Press, 1982.
12. Brennan, P.J. and Kroliczek, E.J., Heat Pipe Design Handbook, Vols. 1 and 2, B & K Engineering, Inc., NTIS n81-700113, 1979.
13. Tien, C.L., Fluid Mechanics of Heat Pipe, Ann. Rev. Fluid Mech. Vol. 7, pp. 167-185, 1975.
14. Marcus, B.D., Theory and Design of Variable Conductance Heat Pipes, NASA CR-2018, 1972.