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Summary

A new version of the NASA Glenn Steady State Heat Pipe Code, designated “GLENHP,” is introduced here. This represents an update to the disk operating system (DOS) version LERCHP reported in NASA/TM—2000-209807. The new code operates on 32- and 64-bit Windows-based platforms from within the 32-bit command prompt window. An additional evaporator boundary condition and other features are provided.

Introduction

A heat pipe code LERCHP has been developed at the Glenn Research Center over a period of years to facilitate the initial design and evaluation of space power systems (Refs. 1 to 4). Versions of this code were based on the disk operating system (DOS) of personal computers then available and were written using Microsoft compilers based on Fortran 77. In order for LERCHP to be usable on machines with 32- and 64-bit architecture, the source code was revised, updated, and recompiled using Compaq Visual Fortran. This report introduces the recompiled code as GLENHP.

Discussion

Source code for the new Windows-based GLENHP is similar to that used for LERCHP, the DOS version (Refs. 2 and 3). The mode of keyboard data input for GLENHP is essentially the same as that used in LERCHP, as described in References 2 and 3.

Reference 4 contains a detailed description of the structure of the source code, including flow charts showing the manner in which a solution is obtained. The essential equations employed in computing the liquid, vapor, and thermal flows in a heat pipe are also shown. Simple equations for the performance limits (capillary, entrainment, etc.) are given. A description of the algorithm employed in computing a heat pipe run is presented. Listings of the subroutine names and variable names employed in the source code are contained in References 3 and 4. Examples of data input and output from the console are also shown.

In the previous DOS code of LERCHP (Refs. 2 and 3) two options were provided for the evaporator heat input: (1) specified heat input and (2) heat transfer from the environment by radiation and/or convection. In the present code GLENHP, fixed evaporator surface temperature is added as a third heat input condition. This feature is prompted by laboratory heat pipe tests, where the evaporator is often clamped in a heated block such that the heat pipe evaporator surface temperature is at a fixed and known value.

A change in the manner of data output has been made in the new code GLENHP. The DOS-based LERCHP used a dedicated printer to produce a running log of data input and output. The new code creates a file HPOutput.txt. The user can then request the production of a text file. Alternatively, the user can create graphical outputs from HPOutput.txt.

GLENHP should only be used to obtain a first approximation for any heat pipe design problem. Of necessity, a limited number of pipe parameters are employed in the code. The code provides for changes in these parameters as a user option. Published sources should be referred to for a variety of these in refining a design. Among these are wick thermal conductivity, permeability, entrainment, and the onset of boiling. Reference 5 is one source for some of these.

The code will provide a simple view of a heat pipe for situations where the user provides thermal boundary conditions to obtain a preliminary estimate of pipe performance. The role of any heat pipe in a system or structure whose thermal conditions are being evaluated requires the use of a commercially available code. This requirement is beyond the scope of GLENHP.

Liquid Pressure in Wicking

During execution of the code, circumstances can arise where the liquid pressure in the wicking can locally exceed the vapor pressure adjacent. Ernst (Ref. 6) identified this situation in an analytical study of the pressures within a heat pipe. He ascribed it to the possibility of vapor pressure recovery in the condenser. Ernst in his incompressible analysis elected to assume the equality of liquid and vapor pressures in the condenser. This effect has subsequently been neglected normally as a factor in heat pipe operation (Ref. 5, pages 27 and 28, and Ref. 6). However, if the wick liquid pressure exceeds the vapor pressure, this condition—if encountered in actual practice—could be detrimental to heat pipe operation. Liquid may be stripped from the wick interior into high-velocity vapor streams. A malfunction or operational failure of the pipe can then result. Whether this adverse differential of liquid and vapor pressure represents a serious situation in the heat pipes may be debated. This pressure differential is accounted for in GLENHP, since the code was derived to handle compressibility. During code execution it is defined as the occurrence of a wet point. If it were to be encountered in practice, the experimenter would possibly identify it as being related to entrainment. The present code separately identifies entrainment as stripping of liquid from wick pores due to vapor flow. However, if the wet point phenomenon is a factor, it is not identified in the code as being related to entrainment. Examples of data input resulting in identification of wet points follow in the appendixes.

It is often assumed that the pressures in the vapor and the wicking are equal at the end of the condenser. If there is even the slightest excess liquid at this point, a meniscus the diameter of the vapor space could exist with a corresponding pressure differential between liquid and vapor. The code makes this assumption unless a wet point is identified, signifying liquid outside the wick. If a wet point is found, the code assumes that liquid and vapor pressures are the same at the condenser end.

Execution of GLENHP

The executable code that has been provided by a Compaq Visual Fortran compiler runs on a 32-bit machine in the usual fashion by typing GLENHP. However, this same executable code if loaded on a 64-bit machine can be run from the 32-bit command prompt window CMD.EXE that is located in the directory C:\Windows\System32:

(1) The user launches CMD.EXE.
(2) A pop-up window appears on the screen.
(3) The user launches GLENHP from within the 32-bit CMD.EXE window.
(4) Execution of a desired case produces the output file HPOutput.txt.
(5) The user accesses this file to create a printout or graphical displays.

Examples of Code Operation

Some examples have been prepared to illustrate the operation of the code. For these examples, when the GLENHP software is first started, it requests data input such as that presented in Appendix A for the first case. These examples are not representative of any real heat pipe application but are only intended to illustrate a portion of code capability. The example, Appendix A, is for a pipe whose heat source is a closely fitted circumferential radiation heater at a uniform temperature. The data produced in the file HPOutput.txt for the example of Appendix A are shown in Appendix B. A portion of the data generated by the solution are then employed in a second example to provide a case in which nonuniform evaporator heat input is specified, as shown in Appendix C. Appendix D illustrates the entry of data for a bent pipe in a gravitational field (g) such that the orientation of the pipe is expressed as the distance below a horizon. This causes the presence of a wet point. Also presented in Appendix D is a case in which the occurrence of a wet point is caused in 0g by a particular choice of wick. In Appendix E the bent pipe data of Appendix D are input as pipe angles below the horizon instead of distance, demonstrating an option available in the code.

Appendix F contains an example of a heat pipe with a square evaporator, round adiabatic and condenser sections, and an artery the entire length. For the square section the code approximates the vapor flow situation by means of the wetted perimeter approximation incorporated in the code.

Concluding Remarks

The new GLENHP heat pipe code has been organized to enable changes in some input variables without reentering the entire data set. A heat pipe designer can thus search quickly for possible heat pipe configurations that can be refined by recourse to more elegant data algorithms available in the literature. Also, the documented source code can be modified by the incorporation of such algorithms and recompiled to provide solutions aligned with the user’s needs.

Appendix A.—Radiation Heating of Evaporator

A close-fitted heater radiating to the evaporator as in laboratory testing is assumed. End losses are neglected. A cylindrical artery partially embedded in two wraps of screen wicking is attached to the length of the pipe. The condenser is finned to increase the effective radiation heat transfer area to the environment. Assumed dimensions of the pipe interior are listed in the following tabulation. GLENHP requests the following data to be entered for this case when prompted on the screen. Definitions of the requested parameters are contained in extensive listing contained in Reference 4.

"g" field strength, fraction of "g"	0	
Straight Pipe		
Initial # of Runge-Kutta steps	100	default
Number of data points output	20	
Number of thermal sections	3	
Pipe dimensions same in all sections		
Artery protrudes into vapor space		
Outside wall diameter, m	0.0191	
Inside wall diameter, m	0.0175	
Screen wick with artery		
Wick properties do not differ in sections		
Screen wire diameter, m	$2.54\text{x}10^{-5}$	
Space between wires, m	$3.81\text{x}10^{-5}$	
Crimping factor	1.05	default
Screen wraps	2	
Number of arteries	1	
Artery inside diameter, m	$1.346\text{x}10^{-3}$	
Artery vapor blockage, m^2	$2.01\text{x}10^{-6}$	
Artery perimeter in vapor flow, m	$5.027\text{x}10^{-3}$	
Nucleation radius, m	1x10-6	default
Stainless steel pipe		
Stainless steel wick		
Sodium working fluid		
Wetting angle, degree	0	default
Weber number	6.283	default
Thermal conditions section 1		
Heater temperature	1510 K	
Constant section properties		
Section end, m	0.2	
Specific area, m^2/m	0.06	
Radk	0.8	
HC, W/m^2K	0	
Thermal conditions section 2 (adiabatic)		
Heat input		
Constant section properties		
Section end, m	0.4	
Heat input, W	0	
Thermal conditions section 3		
Environment temperature specified		
Constant section properties		
Section end, m	1.0	
Environment temperature, K	273	
Specific area per unit length, m^2/m	0.15	
Radiation factor, Radk	0.8	
Convection coefficient, W/m^2	0	

Execution of the data input using this example results in the output listed in Appendix B.

Appendix B.—Data Output for Radiation Case of Appendix A

The data input and output in the radiation case of Appendix A are listed here. Some of the resulting thermal data are used to generate an example for Appendix C of specified heat input to the evaporator rather than heat input from a radiation heater. For brevity, the number of data points along the pipe for sections 2 and 3 are set at 10.

Particular attention is called to the data output for the end of the pipe at $z = 1.0$. The vapor pressure is listed as 4183 N/m^2 and the liquid pressure as 4151 N/m^2. This is due to the assumption that at the end of the condenser, a fillet exists at the inside diameter of the pipe. At this condition, the liquid pressure is less than the vapor pressure by roughly the capillary pressure difference $\Delta p = 4\,\sigma/d$, where σ is the local surface tension and d is the approximate inside pipe diameter.

```
GLENHP HEAT PIPE CODE,NASA GLENN RESEARCH CENTER

TURBULENCE CONSIDERED IN LAST CONDENSER

BEGIN LISTING OF INPUT DATA

"G" FIELD STRENGTH,FRACTIONS OF "G"        0.0000000

INITIAL # OF RUNGE-KUTTA STEPS CHOSEN   100
NUMBER OF DATA POINTS OUTPUT ALONG PIPE  20
NUMBER OF THERMAL SECTIONS IN THE PIPE    3
CIRCULAR SECTION,ARTERIES PROTRUDE INTO VAPOR
SCREEN WICK WITH ARTERIES
SCREEN WIRE DIAMETER,DIAM, m       0.25400001E-04
SPACE BETWEEN WICK WIRES,WIDE, m   0.38099999E-04
CRIMPING FACTOR                     1.0500000
NUMBER OF SCREEN WRAPS,NUMWRP,       2
NUMBER OF ARTERIES IN SECTION, NA    1
ARTERY INSIDE DIAMETER,DAI, m            0.13460000E-02
VAPOR BLOCKAGE BY EACH ARTERY,APP, m**2  0.20099999E-05
ARTERY PERIMETER IN VAPOR FLOW,PER, m    0.50269999E-02

ALL WICKING,X-SECTION DIMENSIONS SAME AS THERMAL SECTION 1
SCREEN WICK WITH ARTERIES SUBROUTINE
DO=   0.1910000E-01 DI=   0.1750000E-01 TWI=   0.1016000E-03
AK=   0.8064128E-13 PE=   0.5936646E-01 PORE=  0.6701331
AV=   0.2329647E-03 RCM=  0.1905000E-04
DWBR= 0.3810000E-04 RSS=   0.000000     RN=    0.1000000E-05

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  ENVIRONMENT OR HEATER TEMPERATURE SPECIFIED IN THIS
SECTION
ZI(1)   0.0000000     ZI(2)  0.20000000
  SA= 0.59999999E-01 RADK= 0.80000001    HC=  0.0000000    TENV=  1510.0000

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)   1.0000000
  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 AT EVAP TOP
  P - PLTOP, N/m**2         =         1897.6665
CAPILLARY LIMIT  PC, N/m**2 =         14526.531

BEGIN SECTION # 1

Z=      0.0000000     P=       4856.2129     PL=      2958.5464
T1Z=    897.08563     T4Z=     906.09375     TM=      897.08563
VM=     0.0000000     MACHM=   0.0000000     A=      0.56590277
DQDZ=   12445.024     Q=       0.0000000

Z=     0.50000001E-01 P=       4825.3979     PL=      2968.8403
T1Z=    896.66736     T4Z=     905.68512     TM=      896.41522
VM=     40.531361     MACHM=  0.67083761E-01 A=      0.55235010
DQDZ=   12449.333     Q=       622.31598

Z=     0.10000000     P=       4720.4102     PL=      3003.2021
T1Z=    895.22498     T4Z=     904.27509     TM=      894.04822
VM=     82.621643     MACHM=  0.13700800     A=      0.56787127
DQDZ=   12462.154     Q=       1245.0210

Z=     0.15000001     P=       4531.2305     PL=      3062.2944
T1Z=    892.55560     T4Z=     901.66614     TM=      889.63947
VM=     128.38832     MACHM=  0.21366450     A=      0.59369910
DQDZ=   12484.926     Q=       1868.5631

Z=     0.20000000     P=       4238.4932     PL=      3146.4602
T1Z=    888.23206     T4Z=     897.43927     TM=      882.42041
VM=     181.30273     MACHM=  0.30352971     A=      0.63523388
DQDZ=   12514.847     Q=       2493.5010
```

```
BEGIN SECTION # 2
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =         1092.0315
CAPILLARY LIMIT  PC, N/m**2 =         14611.117
Z=     0.20000000     P=       4238.4917     PL=       3146.4602
T1Z=    888.23206     T4Z=     888.23206     TM=       882.42041
VM=     181.30273     MACHM=  0.30352971     A=      0.63523388
DQDZ=   0.0000000     Q=       2493.5010

Z=     0.30000001     P=       4155.2915     PL=       3345.2727
T1Z=    886.95673     T4Z=     886.95673     TM=       881.58350
VM=     184.89436     MACHM=  0.30955526     A=      0.54240239
DQDZ=   0.0000000     Q=       2493.5010

Z=     0.40000001     P=       4074.3271     PL=       3544.2275
T1Z=    885.69464     T4Z=     885.69464     TM=       880.78931
VM=     188.54225     MACHM=  0.31566089     A=      0.47198483
DQDZ=   0.0000000     Q=       2493.5010

BEGIN SECTION # 3
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =         530.10059
CAPILLARY LIMIT  PC, N/m**2 =         14635.357

Z=     0.40000001     P=       4074.3281     PL=       3544.2275
T1Z=    885.69464     T4Z=     882.62860     TM=       880.78931
VM=     188.54225     MACHM=  0.31566089     A=       *********
DQDZ=  -4134.8052     Q=       2493.5010

Z=     0.50000000     P=       4105.4390     PL=       3728.0933
T1Z=    886.18213     T4Z=     883.11249     TM=       884.62219
VM=     157.28496     MACHM=  0.26209491     A=       *********
DQDZ=  -4143.6401     Q=       2079.6047

Z=     0.60000002     P=       4135.3799     PL=       3878.6050
T1Z=    886.64832     T4Z=     883.57495     TM=       886.64832
VM=     125.53560     MACHM=  0.20870291     A=       *********
DQDZ=  -4152.4971     Q=       1664.7627

Z=     0.70000005     P=       4156.2217     PL=       3996.1235
T1Z=    886.97113     T4Z=     883.89508     TM=       886.97113
VM=     93.855392     MACHM=  0.15601297     A=       *********
DQDZ=  -4158.6333     Q=       1249.1902

Z=     0.80000007     P=       4171.0771     PL=       4080.6765
T1Z=    887.20038     T4Z=     884.12250     TM=       887.20038
VM=     62.516827     MACHM=  0.10390959     A=       *********
DQDZ=  -4163.0107     Q=       833.09253

Z=     0.90000010     P=       4180.0840     PL=       4132.2461
T1Z=    887.33905     T4Z=     884.25995     TM=       887.33905
VM=     31.401892     MACHM=  0.52190155E-01 A=       *********
DQDZ=  -4165.6792     Q=       416.64297
```

```
Z=       1.0000000     P=       4183.3164     PL=      4150.8364
T1Z=     887.38873     T4Z=     884.30927     TM=      887.38873
VM=      *********     MACHM=   *********     A=       *********
DQDZ=  -4166.6694      Q=      0.11382652E-01
TBOIL(1)  0.49891233    DELTCR   3720.5415
TBOIL IS GRADIENT ACROSS LIQUID, DELTCR IS THEORETICAL GRADIENT NEEDED TO
BOIL

SUMMARY
HEATER TEMPERATURE, K                    1510.0000
EVAPORATOR UPSTREAM SURFACE TEMP, K      906.09375
EVAPORATOR UPSTREAM VAPOR TEMP, K        897.08563
CONDENSER DOWNSTREAM SURFACE TEMP,K      884.30927
CONDENSER DOWNSTREAM VAPOR TEMP, K       887.38873
TOTAL HEAT INPUT TO PIPE, WATTS          2493.5010
MAXIMUM MEAN MACH NUMBER IN PIPE        0.31566089
MAXIMUM MENISCUS PRESS.DIFFERENCE
  P - PLTOP, n/m**2 =                    1897.6665
CAPILLARY LIMIT  PC,N/m**2               14526.531

CASE FINISHED
```

Appendix C.—Specified Heat Input to Evaporator

This appendix illustrates the entry of thermal data for the case of specified heat input to the evaporator. The heat pipe physical specifications are the same as those listed in Appendix A and tabulated in Appendix B. However, rather than radiation heat input, the varied evaporator heat input determined from that example are used as the specified evaporator heat inputs for this case. The thermal data of section 1 (evaporator) output as DQDZ in Appendix B are entered as heat input DQI at 5 specified points. At execution, the code spline fits the variables DQI for integrating through the evaporator. Thermal conditions for sections 2 and 3 are as in Appendix A. Again, for brevity, the data for sections 2 and 3 are listed as though only 10 data points were selected for output rather than 20 as indicated in Appendix A.

As might be expected, the output for this case closely resembles that of the radiation case, Appendix B, illustrating the satisfactory performance of the spline fit routine as applied to the evaporator heat input data.

```
SECTION NUMBER  1  HEAT INPUT SPECIFIED IN THIS SECTION
# OF POINTS IN SECTION( 1)= 5
I= 1 Z=   0.0000000    DQI=   12445.024
I= 2 Z=  0.50000001E-01DQI=   12449.333
I= 3 Z=  0.10000000    DQI=   12462.154
I= 4 Z=  0.15000001    DQI=   12484.926
I= 5 Z=  0.20000000    DQI=   12514.847

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)   1.0000000
  SA= 0.15000001     RADK= 0.80000001    HC=  0.0000000    TENV=  273.00000

THERMAL CONVERGENCE GOOD,WITHIN RANGE:
  1E-4<Q/QIN<.0005

BEGIN PRINTOUT OF RESULTS
MENISCUS PRESS.DIFFERENCE AT EVAP TOP
  P - PLTOP, N/m**2         =         1898.1704
CAPILLARY LIMIT  PC, N/m**2 =         14526.860

BEGIN SECTION # 1

Z=       0.0000000     P=       4853.6733     PL=      2955.5029
T1Z=     897.05127     T4Z=     906.05988     TM=      897.05127
VM=      0.0000000     MACHM=   0.0000000     A=      0.56590372
DQDZ=    12445.024     Q=       0.0000000

Z=      0.10000000     P=       4717.7954     PL=      3000.1594
T1Z=     895.18884     T4Z=     904.23706     TM=      894.01111
VM=      82.662239     MACHM=  0.13707787     A=      0.56788737
DQDZ=    12458.768     Q=       1244.9989
```

```
Z=      0.20000000     P=       4235.6562     PL=       3143.4177
T1Z=     888.18896     T4Z=     897.39697     TM=       882.37158
VM=      181.40250     MACHM=  0.30370548     A=      0.63531482
DQDZ=    12514.847     Q=       2493.3547

BEGIN SECTION # 2
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =         1092.2400
CAPILLARY LIMIT  PC, N/m**2 =         14611.528

Z=      0.20000000     P=       4235.6577     PL=       3143.4177
T1Z=     888.18896     T4Z=     888.18896     TM=       882.37158
VM=      181.40250     MACHM=  0.30370548     A=      0.63531482
DQDZ=    0.0000000     Q=       2493.3547

Z=      0.30000001     P=       4152.4038     PL=       3342.2251
T1Z=     886.91211     T4Z=     886.91211     TM=       881.53345
VM=      185.00067     MACHM=  0.30974233     A=      0.54249471
DQDZ=    0.0000000     Q=       2493.3547

Z=      0.40000001     P=       4071.3870     PL=       3541.1750
T1Z=     885.64838     T4Z=     885.64838     TM=       880.73853
VM=      188.65582     MACHM=  0.31586018     A=      0.47209266
DQDZ=    0.0000000     Q=       2493.3547

BEGIN SECTION # 3
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =         530.21167
CAPILLARY LIMIT  PC, N/m**2 =         14635.801

Z=      0.40000001     P=       4071.3867     PL=       3541.1750
T1Z=     885.64838     T4Z=     882.58270     TM=       880.73853
VM=      188.65582     MACHM=  0.31586018     A=       *********
DQDZ=   -4133.9365     Q=       2493.3547

Z=      0.50000000     P=       4102.4766     PL=       3725.0383
T1Z=     886.13580     T4Z=     883.06653     TM=       884.57465
VM=      157.38554     MACHM=  0.26226887     A=       *********
DQDZ=   -4142.7695     Q=       2079.5452

Z=      0.60000002     P=       4132.4067     PL=       3875.5530
T1Z=     886.60217     T4Z=     883.52911     TM=       886.60217
VM=      125.62152     MACHM=  0.20885046     A=       *********
DQDZ=   -4151.6289     Q=       1664.7902

Z=      0.70000005     P=       4153.2422     PL=       3993.0806
T1Z=     886.92511     T4Z=     883.84943     TM=       886.92511
VM=      93.926689     MACHM=  0.15613489     A=       *********
DQDZ=   -4157.7661     Q=       1249.3043

Z=      0.80000007     P=       4168.0908     PL=       4077.6489
T1Z=     887.15436     T4Z=     884.07684     TM=       887.15436
VM=      62.573692     MACHM=  0.10400640     A=       *********
DQDZ=   -4162.1431     Q=       833.29352
```

```
Z=     0.90000010     P=       4177.0991     PL=      4129.2393
T1Z=    887.29315     T4Z=     884.21442     TM=      887.29315
VM=     31.444498     MACHM=  0.52262139E-01 A=       *********
DQDZ=  -4164.8135     Q=       416.93073

Z=      1.0000000     P=       4180.3374     PL=      4147.8564
T1Z=    887.34296     T4Z=     884.26385     TM=      887.34296
VM=     *********     MACHM=   *********     A=       *********
DQDZ=  -4165.8047     Q=      0.38556227

TBOIL(1)  0.49890652    DELTCR   3722.2729
TBOIL IS GRADIENT ACROSS LIQUID, DELTCR IS THEORETICAL GRADIENT NEEDED TO
BOIL

SUMMARY
EVAPORATOR UPSTREAM SURFACE TEMP, K   906.05988
EVAPORATOR UPSTREAM VAPOR TEMP, K     897.05127
CONDENSER DOWNSTREAM SURFACE TEMP,K   884.26385
CONDENSER DOWNSTREAM VAPOR TEMP, K    887.34296
TOTAL HEAT INPUT TO PIPE, WATTS       2493.3547
MAXIMUM MEAN MACH NUMBER IN PIPE     0.31586018
MAXIMUM MENISCUS PRESS.DIFFERENCE
  P - PLTOP, n/m**2 =                 1898.1704
CAPILLARY LIMIT  PC,N/m**2            14526.860

CASE FINISHED
```

Appendix D.—Excess Liquid Pressure in Wicking

Possible causes of excess liquid pressure in wicking are as follows: (1) elevation of a portion of the pipe in a gravitational field (g) above the evaporator, resulting in excess hydrostatic pressure in the returning liquid and (2) choice of or lack of adequate liquid wicking. Whether the latter is an artifact of the present code is unknown. Examples of both of these situations are presented below. When they occur in the code their onset is identified by a statement of WET POINT ENCOUNTERED, a convenient description of the condition described. This condition may also be referred to as “flooding of the condenser.”

(a) Bent Pipe in a Gravitational Field

For this example a partially bent pipe lying in a 1g field out of the horizontal plane is assumed. It is not representative of any real heat pipe application but is only intended to illustrate a portion of code capability. The following data and instructions below are the initial data entered at input when prompted on the screen:

```
“g” field strength, fractions of “g”                 1.0
Pipe is not straight
Curved or bent pipe
Local angle is not specified
Number of discrete curved or bent sections           2
Locations with input data in Section 1               3
   Axial distance, m   Height above horizon, m
          0                      0
          0.2                   -0.02
          0.3                   -0.025
Locations with input data in Section 2               9
   Axial distance, m   Height above horizon, m
          0.3                   -0.025
          0.35                  -0.024
          0.4                   -0.02
          0.5                   -0.015
          0.6                   -0.01
          0.7                    0
          0.8                    0.01
          0.9                    0.02
          1.0                    0.03
Initial # of Runge-Kutta steps                       100 default
Number of data points output                         10
```

The remainder of the input data are as listed for the example of Appendix A except that a constant heat input of 2500 W is entered for the evaporator of length 0.2 m. Completed entry of these data results during execution in the message “WET POINT ENCOUNTERED, MAKE OTHER CHANGE.” However, the code continues the execution. Comparison of the local liquid pressures PLTOP with the local vapor pressure P reveal the portion of the pipe experiencing the wet point:

```
THERMAL CONVERGENCE EXCELLENT,Q/QIN<.0001
WET POINT ENCOUNTERED
ALTER PIPE LENGTH,GEOMETRY,OR "g" FIELD LOCATION
DATA ALONG PIPE AT WET POINT CONDITION FOLLOWS:
```

```
BEGIN PRINTOUT OF RESULTS
MENISCUS PRESS.DIFFERENCE AT EVAP TOP
  P - PLTOP, N/m**2         =        1626.2158
CAPILLARY LIMIT  PC, N/m**2 =        14522.090

BEGIN SECTION # 1

Z=     0.0000000
P=      4890.6538     PLBOT=   3399.7407     PLTOP=   3264.4380
T1Z=    897.55048     T4Z=     906.59088     TM=      897.55048
VM=     0.0000000     MACHM=   0.0000000     A=      0.56625521
DQDZ=   12500.000     Q=       0.0000000     HITE=    0.0000000

Z=    0.10000000
P=      4754.7070     PLBOT=   3533.2751     PLTOP=   3397.7832
T1Z=    895.69922     T4Z=     904.76904     TM=      894.52832
VM=     82.399513     MACHM=  0.13660735     A=      0.56808478
DQDZ=   12500.000     Q=       1249.9999     HITE=  -0.11249999E-01

Z=    0.20000000
P=      4274.3726     PLBOT=   3746.1077     PLTOP=   3610.1775
T1Z=    888.77545     T4Z=     897.96222     TM=      883.01892
VM=     180.38199     MACHM=  0.30188519     A=      0.63447052
DQDZ=   12500.000     Q=       2500.0010     HITE=  -0.19999998E-01

BEGIN SECTION # 2
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =        664.19458
CAPILLARY LIMIT  PC, N/m**2 =        14605.925

Z=    0.20000000
P=      4274.3721     PLBOT=   3746.1077     PLTOP=   3610.1775
T1Z=    888.77545     T4Z=     888.77545     TM=      883.01892
VM=     180.38199     MACHM=  0.30188519     A=      0.63447052
DQDZ=   0.0000000     Q=       2500.0010     HITE=  -0.19999998E-01

Z=    0.30000001
P=      4191.7251     PLBOT=   3984.7041     PLTOP=   3847.9534
T1Z=    887.51782     T4Z=     887.51782     TM=      882.19696
VM=     183.90196     MACHM=  0.30778721     A=      0.54169923
DQDZ=   0.0000000     Q=       2500.0010     HITE=  -0.24860913E-01

Z=    0.40000001
P=      4111.3452     PLBOT=   4144.6890     PLTOP=   4008.3218
T1Z=    886.27429     T4Z=     886.27429     TM=      881.41827
VM=     187.47322     MACHM=  0.31376091     A=      0.47122380
DQDZ=   0.0000000     Q=       2500.0010     HITE=  -0.19878870E-01
```

```
BEGIN SECTION # 3
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =        103.02002
CAPILLARY LIMIT  PC, N/m**2 =        14629.821

Z=    0.40000001
P=      4111.3418     PLBOT=   4144.6890     PLTOP=   4008.3218
T1Z=    886.27429     T4Z=     883.20367     TM=      881.41827
VM=     187.47322     MACHM=  0.31376091     A=       *********
DQDZ=  -4145.6909     Q=       2500.0010     HITE=  -0.19878870E-01

Z=    0.50000000
P=      4142.6353     PLBOT=   4289.6772     PLTOP=   4152.8809
T1Z=    886.76086     T4Z=     883.68658     TM=      885.21240
VM=     156.38242     MACHM=  0.26051369     A=       *********
DQDZ=  -4154.5259     Q=       2085.0156     HITE=  -0.14566304E-01

Z=    0.60000002
P=      4172.6636     PLBOT=   4400.7637     PLTOP=   4264.2886
T1Z=    887.22479     T4Z=     884.14679     TM=      887.22479
VM=     124.81553     MACHM=  0.20744869     A=       *********
DQDZ=  -4163.3589     Q=       1669.0863     HITE=  -0.91749206E-02

Z=    0.70000005
P=      4193.5630     PLBOT=   4439.2637     PLTOP=   4303.1543
T1Z=    887.54602     T4Z=     884.46545     TM=      887.54602
VM=     93.318336     MACHM=  0.15507753     A=       *********
DQDZ=  -4169.4766     Q=       1252.4287     HITE=   0.10420510E-02

Z=    0.80000007
P=      4208.4634     PLBOT=   4444.9082     PLTOP=   4308.6895
T1Z=    887.77429     T4Z=     884.69177     TM=      887.77429
VM=     62.158360     MACHM=  0.10328539     A=       *********
DQDZ=  -4173.8428     Q=       835.24731     HITE=   0.10983814E-01

Z=    0.90000010
P=      4217.4946     PLBOT=   4417.4395     PLTOP=   4281.2495
T1Z=    887.91223     T4Z=     884.82861     TM=      887.91223
VM=     31.219460     MACHM=  0.51872734E-01 A=       *********
DQDZ=  -4176.5034     Q=       417.71512     HITE=   0.20999789E-01

Z=     1.0000000
P=      4220.7329     PLBOT=   4356.9326     PLTOP=   4220.7329
T1Z=    887.96167     T4Z=     884.87762     TM=      887.96167
VM=     *********     MACHM=   *********     A=       *********
DQDZ=  -4177.4893     Q=      0.14177973E-02 HITE=   0.30121177E-01

TBOIL(1)  0.50119513    DELTCR   3700.7407
TBOIL IS GRADIENT ACROSS LIQUID, DELTCR IS THEORETICAL GRADIENT NEEDED TO
BOIL
```

```
SUMMARY
EVAPORATOR UPSTREAM SURFACE TEMP, K   906.59088
EVAPORATOR UPSTREAM VAPOR TEMP, K     897.55048
CONDENSER DOWNSTREAM SURFACE TEMP,K   884.87762
CONDENSER DOWNSTREAM VAPOR TEMP, K    887.96167
TOTAL HEAT INPUT TO PIPE, WATTS       2500.0010
MAXIMUM MEAN MACH NUMBER IN PIPE     0.31376091
MAXIMUM MENISCUS PRESS.DIFFERENCE
  P - PLTOP, n/m**2 =                 1626.2158
CAPILLARY LIMIT  PC,N/m**2            14522.090
WET POINT ENCOUNTERED. CHANGE PIPE LENGTH,GEOMETRY OR CHANGE ORIENTATION IN
"g" FIELD
```

(b) Wicking choice

This example considers a straight stainless pipe in 0g with no artery. The lengths are evaporator 0.2 m, adiabatic section 0.2 m, and condenser 0.6 m. The condenser environment specified in Appendix A applies. Pipe outside and inside diameters are 0.0191 and 0.0175 m, respectively. The sintered metal wick has these properties: wick thickness (TWI) 0.001 m, porosity (PORE) 0.065, and particle diameter (RSS) 0.0005 m. The wick thermal conductivity constant (WICCON) is 0.53.

Execution of the code at evaporator heat input of 600 W provides the following results. In this 0g case the wick liquid pressure PL is to be compared to vapor pressure P.

```
THERMAL CONVERGENCE EXCELLENT,Q/QIN<.0001
WET POINT ENCOUNTERED
ALTER PIPE LENGTH,GEOMETRY,OR "g" FIELD LOCATION
DATA ALONG PIPE AT WET POINT CONDITION FOLLOWS:

BEGIN PRINTOUT OF RESULTS
MENISCUS PRESS.DIFFERENCE AT EVAP TOP
  P - PLTOP, N/m**2         =         233.75073
CAPILLARY LIMIT  PC, N/m**2 =         1411.5743

BEGIN SECTION # 1

Z=      0.0000000     P=       1542.6198     PL=      1308.8690
T1Z=    827.62231     T4Z=     834.82214     TM=      827.62231
VM=     0.0000000     MACHM=   0.0000000     A=      0.49270344
DQDZ=   6000.0000     Q=       0.0000000

Z=     0.39999999E-01 P=       1519.5116     PL=      1309.2429
T1Z=    826.78052     T4Z=     833.99969     TM=      826.25714
VM=     56.353600     MACHM=  0.96605778E-01 A=      0.50267476
DQDZ=   6000.0000     Q=       240.00000

Z=     0.79999998E-01 P=       1442.0148     PL=      1310.4380
T1Z=    823.87463     T4Z=     831.16217     TM=      821.48755
VM=     117.93011     MACHM=  0.20301300     A=      0.53587651
DQDZ=   6000.0000     Q=       480.00003

Z=     0.10000000     P=       1378.5164     PL=      1311.3483
T1Z=    821.39130     T4Z=     828.73901     TM=      817.36456
VM=     153.25409     MACHM=  0.26479375     A=      0.56422204
DQDZ=   6000.0000     Q=       600.00043
```

```
BEGIN SECTION # 2
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =        67.167969
CAPILLARY LIMIT  PC, N/m**2 =        1417.1062

Z=      0.10000000     P=       1378.5162     PL=       1311.3483
T1Z=     821.39130     T4Z=     821.39130     TM=       817.36456
VM=      153.25409     MACHM=  0.26479375     A=       0.56422204
DQDZ=    0.0000000     Q=       600.00043
Z=      0.12000000     P=       1365.5928     PL=       1312.3846
T1Z=     820.87378     T4Z=     820.87378     TM=       817.07751
VM=      154.70505     MACHM=  0.26728410     A=       0.50521410
DQDZ=    0.0000000     Q=       600.00043

Z=      0.16000000     P=       1340.6135     PL=       1314.4585
T1Z=     819.86139     T4Z=     819.86139     TM=       816.55707
VM=      157.60258     MACHM=  0.27224061     A=       0.41360062
DQDZ=    0.0000000     Q=       600.00043

Z=      0.20000000     P=       1316.4644     PL=       1316.5332
T1Z=     818.86707     T4Z=     818.86707     TM=       816.09692
VM=      160.52592     MACHM=  0.27722013     A=       0.34785968
DQDZ=    0.0000000     Q=       600.00043

BEGIN SECTION # 3
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =      -0.68359375E-01
CAPILLARY LIMIT  PC, N/m**2 =        1419.3472

Z=      0.20000000     P=       1316.4648     PL=       1316.5332
T1Z=     818.86707     T4Z=     815.16180     TM=       816.09692
VM=      160.52592     MACHM=  0.27722013     A=        *********
DQDZ=   -2997.8770     Q=       600.00043

Z=      0.23999998     P=       1318.3982     PL=       1318.4175
T1Z=     818.94727     T4Z=     815.24164     TM=       819.04468
VM=      129.12001     MACHM=  0.22203851     A=        *********
DQDZ=   -2999.0134     Q=       480.07031

Z=      0.27999997     P=       1319.8837     PL=       1319.8883
T1Z=     819.00879     T4Z=     815.30280     TM=       819.00879
VM=      96.803619     MACHM=  0.16647907     A=        *********
DQDZ=   -2999.9480     Q=       360.09009

Z=      0.31999996     P=       1320.9458     PL=       1320.9458
T1Z=     819.05273     T4Z=     815.34650     TM=       819.05273
VM=      64.593979     MACHM=  0.11108390     A=        *********
DQDZ=   -3000.6084     Q=       240.07834

Z=      0.35999995     P=       1321.5901     PL=       1321.5902
T1Z=     819.07941     T4Z=     815.37299     TM=       819.07941
VM=      32.437115     MACHM=  0.55782221E-01 A=        *********
DQDZ=   -3001.0110     Q=       120.04535
```

```
Z=     0.40000001     P=       1321.8219     PL=      1321.8219
T1Z=    819.08899     T4Z=     815.38251     TM=      819.08899
VM=     *********     MACHM=   *********     A=       *********
DQDZ=  -3001.1594     Q=      0.11239421E-02

TBOIL(1)   2.1461210    DELTCR   10464.415
TBOIL IS GRADIENT ACROSS LIQUID, DELTCR IS THEORETICAL GRADIENT NEEDED TO
BOIL

SUMMARY
EVAPORATOR UPSTREAM SURFACE TEMP, K   834.82214
EVAPORATOR UPSTREAM VAPOR TEMP, K     827.62231
CONDENSER DOWNSTREAM SURFACE TEMP,K   815.38251
CONDENSER DOWNSTREAM VAPOR TEMP, K    819.08899
TOTAL HEAT INPUT TO PIPE, WATTS       600.00043
MAXIMUM MEAN MACH NUMBER IN PIPE     0.27722013
MAXIMUM MENISCUS PRESS.DIFFERENCE
  P - PLTOP, n/m**2 =                 233.75073
CAPILLARY LIMIT  PC,N/m**2            1411.5743
WET POINT ENCOUNTERED. CHANGE PIPE LENGTH,GEOMETRY OR CHANGE ORIENTATION IN
"g" FIELD


CASE FINISHED
```

Appendix E.—Example of Pipe Orientation Using Angle Instead of Height

In the wet point example of Appendix D the pipe orientation in a gravitational field (g) was determined by specification of height with respect to the gravitational horizon. As an alternative, angle with respect to the horizon can be used instead. For this example the height information of Appendix D was used to compute angles at each of the 12 data points provided in the tabulation therein. For $z = 0$, an angle is computed using the height of –0.02 m at the end of the first increment, $z = 0.2$ thusly: beta = arc sin (–0.02/.2). The following data when requested by GLENHP includes the tabulation of angles versus distance created in this manner.

```
"g" field strength, fractions of "g"             1.0
Pipe is not straight
Curved or bent pipe
Local angle is specified
Number of discrete curved or bent sections       2
Locations with input data in Section 1           3
   Axial distance, m       Angle with horizon
         0                          -5.739
         0.2                        -2.866
         0.3                        -2.866
Locations with input data in Section 2           9
   Axial distance, m       Angle with horizon, beta
         0.3                         1.146
         0.35                        4.589
         0.4                         2.866
         0.5                         2.866
         0.6                         5.739
         0.7                         5.739
         0.8                         5.739
         0.9                         5.739
         1.0                         5.739
Initial # of Runge-Kutta steps                   100 default
             Number of data points output        10
```

If the remainder of the input data are entered as for the example of Appendix D, the resulting solution data will be identical to that produced for the case of Appendix D.

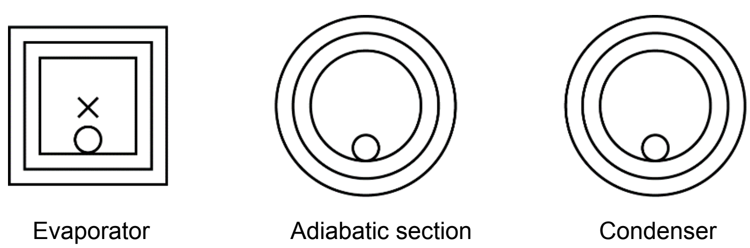
Appendix F.—Round Pipe With Square Evaporator

The code uses the wetted perimeter approximation wherever the vapor state is not completely round, as when a protruding artery is present. This example considers a pipe with round adiabatic and condenser sections and a square evaporator. A single artery within the vapor space traverses the entire pipe. Heat pipes of such configuration have been proposed in the past for use in heat removal from nuclear reactors, for example. The following study is not concerned with the mode of attachment between the square and round sections or the effect on vapor and liquid flow.

For this example a case was run initially for a cylindrical pipe with the following dimensions: external diameter 0.0191 m and inside diameter of 0.0175 m. Two layers of 200-mesh screen wick were assumed on the inside surface with wire diameter of 5.334×10^{-4} m and spacing of 7.366×10^{-4} m with a porosity of 0.6536. Given this input information, the code computed a vapor area of 0.2289×10^{-3} m^2, a wick area-permeability (area × permeability) factor AK of 0.7109×10^{-15} m^4, and a vapor space perimeter of 0.05364 m.

A pipe was then assumed, having adiabatic and condenser sections with the foregoing properties, but having an evaporator of square cross section having the same vapor area. Screen wicking was assumed to be the same in all sections. An AK product of 0.0736×10^{-15} m^4, a vapor space perimeter of 0.06052 m, a wick thickness of 0.2136×10^{-3} m, and a wall thickness of 0.8×10^{-3} m were hand computed for the square evaporator. The centerline of the evaporator was 0.7564×10^{-2} m^4 above the bottom wick surface although in 0g this specification is not required. A circular artery was then applied having an external diameter of 1.6×10^{-3} m, touching the circular wick. The inside diameter of this artery was estimated to be 1.346×10^{-3} m and external diameter, 1.6×10^{-3} m. Vapor area blockage and wetted perimeter addition were computed from this. The AK product for the artery liquid flow, given by $\pi d^4/128$ (d is the approximate inside pipe diameter), was 8.056×10^{-14} m^4. The product AK for the evaporator of necessity will differ from that of the adiabatic and condenser sections. The lengths were evaporator 0.2 m, adiabatic section 0.2 m, and condenser 0.6 m.

The cross sections of the heat pipe being considered then looked like this:



The USER INPUT option was required for the evaporator. With an artery incorporated, the input data for the evaporator was then as follows:

TWALL	0.8000×10^{-3}	wall thickness
CL	0.7564×10^{-2}	centerline to wick (not needed, zero ”g”)
TWI	0.2134×10^{-3}	wick thickness
AK	0.8496×10^{-13}	area-permeability product
PE	0.6553×10^{-1}	vapor space wetted perimeter
PORE	0.6536	porosity of wick
AV	0.2269×10^{-3}	vapor area
RCM	0.3683×10^{-4}	capillary radius
KE	46.57	wick conductivity
DWBR	0.7366×10^{-4}	Weber number

For the adiabatic section and the condenser, the option SCREEN WICK WITH ARTERIES was employed. Much of what was computed by hand for the USER INPUT option was computed by the code for these sections. However, the user was required to furnish some information to the code concerning the presence of the longitudinal artery. From this information, the code computed the decrease in vapor area and the increase in wetted perimeter due to the artery within the vapor space and changed these parameters accordingly. The complete output from the file HPOutput.txt generated at execution is as follows. A portion of the output demonstrates presence of a wet point:

```
GLENHP HEAT PIPE CODE,NASA GLENN RESEARCH CENTER

TURBULENCE CONSIDERED IN LAST CONDENSER

BEGIN LISTING OF INPUT DATA


"G" FIELD STRENGTH,FRACTIONS OF "G"        1.0000000

STRAIGHT PIPE AT ANGLE WITH HORIZON
 (NEGATIVE IS EVAPORATOR UP), BETA,DEG     0.0000000

INITIAL # OF RUNGE-KUTTA STEPS CHOSEN   100
NUMBER OF DATA POINTS OUTPUT ALONG PIPE  10
NUMBER OF THERMAL SECTIONS IN THE PIPE    3
SECTION WICKING AND DIMENSIONS DIFFER

THERMAL SECTION NUMBER  1
NONCIRCULAR PIPE SECTION.ARTERY PRESENCE MUST BEINCLUDED IN AK FURNISHED
USER INPUT WICK DATA
USER INPUT WICK DATA
TWALL=0.8000000E-03 CL=   0.7564000E-02 TWI=   0.2130000E-03
AK=   0.8567000E-13 PE=   0.6553000E-01 PORE=  0.6536000
AV=   0.2269000E-03 RCM=  0.3683000     KE=    46.57000
DWBR= 0.7366000E-04 RSS=   0.000000     RN=    0.1000000E-05

THERMAL SECTION NUMBER  2
CIRCULAR SECTION,ARTERIES PROTRUDE INTO VAPOR
SCREEN WICK WITH ARTERIES
SCREEN WIRE DIAMETER,DIAM, m       0.53339999E-03
SPACE BETWEEN WICK WIRES,WIDE, m   0.73660002E-03
CRIMPING FACTOR                     1.0500000
NUMBER OF SCREEN WRAPS,NUMWRP,       2
NUMBER OF ARTERIES IN SECTION, NA    1
ARTERY INSIDE DIAMETER,DAI, m            0.13460000E-02
VAPOR BLOCKAGE BY EACH ARTERY,APP, m**2  0.20099999E-05
ARTERY PERIMETER IN VAPOR FLOW,PER, m    0.50300001E-02
SCREEN WICK WITH ARTERIES SUBROUTINE
DO=   0.1950000E-01 DI=   0.1750000E-01 TWI=   0.2133600E-02
AK=   0.6397251E-12 PE=   0.4660203E-01 PORE=  0.6536397
AV=   0.1355186E-03 RCM=  0.3683000E-03
DWBR= 0.7366000E-03 RSS=   0.000000     RN=    0.1000000E-05

ARTERY SPECIFICATIONS
VAPOR BLOCKAGE BY ALL ARTERIES, m**2  0.20099999E-05
OUTSIDE PERIMETER OF ALL ARTERIES IN VAPOR FLOW,m  0.50300001E-02
```

```
THERMAL SECTION NUMBER  3
CIRCULAR SECTION,ARTERIES PROTRUDE INTO VAPOR
SCREEN WICK WITH ARTERIES
SCREEN WIRE DIAMETER,DIAM, m       0.53339999E-03
SPACE BETWEEN WICK WIRES,WIDE, m   0.73660002E-03
CRIMPING FACTOR                     1.0500000
NUMBER OF SCREEN WRAPS,NUMWRP,       2
NUMBER OF ARTERIES IN SECTION, NA    1
ARTERY INSIDE DIAMETER,DAI, m            0.13460000E-02
VAPOR BLOCKAGE BY EACH ARTERY,APP, m**2  0.20099999E-05
ARTERY PERIMETER IN VAPOR FLOW,PER, m    0.50300001E-02
SCREEN WICK WITH ARTERIES SUBROUTINE
DO=   0.1950000E-01 DI=   0.1750000E-01 TWI=   0.2133600E-02
AK=   0.6397251E-12 PE=   0.4660203E-01 PORE=  0.6536397
AV=   0.1355186E-03 RCM=  0.3683000E-03
DWBR= 0.7366000E-03 RSS=   0.000000     RN=    0.1000000E-05

ARTERY SPECIFICATIONS
VAPOR BLOCKAGE BY ALL ARTERIES, m**2  0.20099999E-05
OUTSIDE PERIMETER OF ALL ARTERIES IN VAPOR FLOW,m  0.50300001E-02

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=   2500.0000

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)   1.0000000
  SA= 0.15000001     RADK= 0.80000001    HC=  0.0000000    TENV=  273.00000

THERMAL CONVERGENCE EXCELLENT,Q/QIN<.0001
WET POINT ENCOUNTERED
ALTER PIPE LENGTH,GEOMETRY,OR "g" FIELD LOCATION
DATA ALONG PIPE AT WET POINT CONDITION FOLLOWS:

BEGIN PRINTOUT OF RESULTS
MENISCUS PRESS.DIFFERENCE AT EVAP TOP
  P - PLTOP, N/m**2         =        1305.4321
CAPILLARY LIMIT  PC, N/m**2 =       0.74694413
CAPILLARY LIMIT EXCEEDED
```

```
BEGIN SECTION # 1

Z=     0.0000000
P=       5557.8477     PLBOT=   4371.2681     PLTOP=   4252.4155
T1Z=     906.04657     T4Z=     911.58411     TM=      906.04657
VM=      0.0000000     MACHM=   0.0000000     A=      0.56602520
DQDZ=    12500.000     Q=       0.0000000     HITE=    0.0000000

Z=    0.10000000
P=       5427.3794     PLBOT=   4413.2539     PLTOP=   4294.4019
T1Z=     904.45599     T4Z=     910.01202     TM=      903.50061
VM=      74.894127     MACHM=  0.12361052     A=      0.54231942
DQDZ=    12500.000     Q=       1249.9999     HITE=    0.0000000

Z=    0.20000000
P=       4975.0269     PLBOT=   4547.6870     PLTOP=   4428.8345
T1Z=     898.67737     T4Z=     904.30347     TM=      894.10022
VM=      161.31113     MACHM=  0.26824555     A=      0.59725630
DQDZ=    12500.000     Q=       2500.0010     HITE=    0.0000000

BEGIN SECTION # 2
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2         =        546.19385
CAPILLARY LIMIT  PC, N/m**2 =        750.58569

Z=    0.20000000
P=       4975.0283     PLBOT=   4547.6870     PLTOP=   4428.8345
T1Z=     898.67737     T4Z=     898.67737     TM=      894.10022
VM=      161.31113     MACHM=  0.26824555     A=      0.59725630
DQDZ=    0.0000000     Q=       2500.0010     HITE=    0.0000000

Z=    0.30000001
P=       4704.3101     PLBOT=   4565.3911     PLTOP=   4461.0605
T1Z=     895.00128     T4Z=     895.00128     TM=      890.71478
VM=      284.88504     MACHM=  0.47440228     A=      0.55295926
DQDZ=    0.0000000     Q=       2500.0010     HITE=    0.0000000

Z=    0.40000001
P=       4413.6948     PLBOT=   4590.4360     PLTOP=   4486.1055
T1Z=     890.84930     T4Z=     890.84930     TM=      886.70624
VM=      302.62653     MACHM=  0.50487065     A=      0.53163165
DQDZ=    0.0000000     Q=       2500.0010     HITE=    0.0000000
```

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BEGIN SECTION # 3
MENISCUS PRESS.DIFFERENCE AT WICK TOP
  P - PLTOP, N/m**2          =        -72.412598
CAPILLARY LIMIT  PC, N/m**2 =         754.45398

Z=    0.40000001
P=      4413.6929     PLBOT=   4590.4360     PLTOP=   4486.1055
T1Z=    890.84930     T4Z=     883.29358     TM=      886.70624
VM=     302.62653     MACHM=  0.50487065     A=       *********
DQDZ=  -4147.4321     Q=       2500.0010     HITE=    0.0000000

Z=    0.50000000
P=      4412.0054     PLBOT=   4613.7017     PLTOP=   4509.1436
T1Z=    890.82452     T4Z=     883.26947     TM=      890.82452
VM=     254.84711     MACHM=  0.42273274     A=       *********
DQDZ=  -4146.9795     Q=       2085.1680     HITE=    0.0000000

Z=    0.60000002
P=      4437.4302     PLBOT=   4632.7080     PLTOP=   4528.1499
T1Z=    891.19696     T4Z=     883.63269     TM=      891.19696
VM=     203.26459     MACHM=  0.33711559     A=       *********
DQDZ=  -4153.2524     Q=       1670.3429     HITE=    0.0000000

Z=    0.70000005
P=      4492.3774     PLBOT=   4647.5674     PLTOP=   4543.0088
T1Z=    891.99597     T4Z=     884.40912     TM=      891.99597
VM=     151.12833     MACHM=  0.25056162     A=       *********
DQDZ=  -4168.1597     Q=       1254.2313     HITE=    0.0000000

Z=    0.80000007
P=      4531.0083     PLBOT=   4658.2695     PLTOP=   4553.7114
T1Z=    892.55273     T4Z=     884.95007     TM=      892.55273
VM=     100.36338     MACHM=  0.16635688     A=       *********
DQDZ=  -4178.6016     Q=       836.85602     HITE=    0.0000000

Z=    0.90000010
P=      4554.2427     PLBOT=   4664.8101     PLTOP=   4560.2520
T1Z=    892.88556     T4Z=     885.27332     TM=      892.88556
VM=     50.464890     MACHM=  0.83635949E-01 A=       *********
DQDZ=  -4184.8999     Q=       418.64606     HITE=    0.0000000

Z=     1.0000000
P=      4562.6289     PLBOT=   4667.1870     PLTOP=   4562.6289
T1Z=    893.00537     T4Z=     885.38953     TM=      893.00537
VM=     *********     MACHM=   *********     A=       *********
DQDZ=  -4187.2422     Q=      0.57174349E-02 HITE=    0.0000000

TBOIL(1)    1.0574868    DELTCR   3304.6387
TBOIL IS GRADIENT ACROSS LIQUID, DELTCR IS THEORETICAL GRADIENT NEEDED TO
BOIL
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SUMMARY
THERMAL CONVERGENCE FOUND. RESULT MAY NOT BE VALID.CHECK LIMITS.
CAPILLARY LIMIT EXCEEDED.ARTERIES, OR FINER SCREENREQUIRED
EVAPORATOR UPSTREAM SURFACE TEMP, K   911.58411
EVAPORATOR UPSTREAM VAPOR TEMP, K     906.04657
CONDENSER DOWNSTREAM SURFACE TEMP,K   885.38953
CONDENSER DOWNSTREAM VAPOR TEMP, K    893.00537
TOTAL HEAT INPUT TO PIPE, WATTS       2500.0010
MAXIMUM MEAN MACH NUMBER IN PIPE     0.50487065
MAXIMUM MENISCUS PRESS.DIFFERENCE
  P - PLTOP, n/m**2 =                 1305.4321
CAPILLARY LIMIT  PC,N/m**2           0.74694413
ENTRAINMENT LIMIT PROBABLY EXCEEDED.WICKING PORE SIZE IS TOO LARGE AT THIS
COND-  ITION
CAPILLARY LIMIT EXCEEDED.ARTERIES, OR FINER SCREENAND PORES REQUIRED AT THIS
CONDITION
WET POINT ENCOUNTERED. CHANGE PIPE LENGTH,GEOMETRY OR CHANGE ORIENTATION IN
"g" FIELD


CASE FINISHED
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References

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