The Investigation of Entrainment Limit in Operating Heat Pipes

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ABSTRACT

A heat pipe is a two-phase flow heat transfer device that utilizes the latent heat of vaporization of a fluid. It is a sealed container that is lined with a wick structure which is saturated with a selected working fluid. Heat input at one end raises the temperature, which creates an axial pressure gradient and causes the vapor to flow to the opposite end, where heat is rejected and the vapor recondenses. The capillary pumping action provided by the wick structure maintains the circulation of the fluid. At steady-state, the operation of the heat pipe is limited by the occurrence of several phenomena--boiling in the wick, the capillary limit, the sonic limit or the choking of the vapor flow, and the entrainment of liquid droplets in the vapor flow. Of these four limits, the entrainment limit is the least understood. The analytical studies available to date yielded four different equations that predict significantly different maximum heat transfer rates at the onset of entrainment. Therefore, it was the objective of this investigation to compare experimental results to the entrainment limits predicted by these four equations.

In this experiment, liquid droplet entrainment was monitored using a laser beam travelling down the length of the vapor channel to investigate qualitatively the occurrence of entrainment. A graph of the results indicated that the heat flux at the entrainment limit may be at least as great as the lowest value predicted by the four analytical equations. More tests are being conducted to determine the actual entrainment limit in the heat pipe.

The occurrence of slugging affected the heat pipe's operation. Further studies to analytically determine the slugging limit will help in understanding this behavior in an operating heat pipe.

NOMENCLATURE

A	area (m)
D	diameter (m)
g	gravitational acceleration (m/s2)
h_{fg}	heat of vaporization (kJ/kg)
K	thermal conductivity of the wick (W/mK)
L	length (m)
P	pressure (kPa)
Q	heat flux (W)
r	radius (m)
T	temperature (°K)
V	velocity (m/s2)
We	Weber number
Δ	change in, difference
λ	wavelength associated with the liquid surface (m)
ρ	density (kg/m3)
σ	Surface tension (N/m2)

Subscripts

c	capillary,
c	condenser
cm	capillary, maximum
e	evaporator
h	hydraulic
l	liquid
n	nucleation
norm	normal, perpendicular
s	sonic
v	vapor
w	wick

LIST OF FIGURES

OBJECTIVE

It is the objective of this investigation to compare the experimental heat flux with the maximum heat transfer rate at the entrainment limit predicted by analytical equations for an operating heat pipe.

Content

INTRODUCTION

Two types of heat transfer devices that utilize the latent heat of vaporization of a fluid and two-phase flow of liquid are the thermosyphon and the heat pipe. In both thermosyphons and heat pipes the working fluid is chosen such that the operating temperature lies between the critical state and the triple state of the fluid. In the thermosyphon, the condenser is located above the evaporator. Heat input results in the upward flow of the vapor. The vapor then recondenses in the condenser section and is returned to the evaporator by gravity assistance. The use of the gravitational force as the liquid return mechanism in thermosyphons thus dictates that the thermosyphon must be oriented vertically.

Like the thermosyphon, heat input at the evaporator of the heat pipe results in a temperature rise and a corresponding axial pressure gradient, causing the vapor to flow from the evaporator to the condenser. At the condenser, the vapor recondenses and returns to the liquid stream. Unlike the thermosyphon, the heat pipe consists of a sealed container lined with a screen or wick structure. The heat pipe is charged with enough water to saturate the wick. Also, the heat pipe relies on the capillary pressure provided by the wick structure rather than gravitational force to pump the liquid back to the evaporator. Therefore, heat pipes are not limited to the vertical configuration of a thermosyphon.

While thermosyphons have been dated back to the nineteenth century, the first heat pipe patent was awarded to R. S. Gaugler (1944), and the first application of heat pipes was not implemented until twenty years later, at the Los Alamos Scientific Laboratory (Grover, et al., 1964). The heat pipe has several inherent advantages, the most important of which is that heat can be transported a long distance with only a small temperature drop. Therefore, the heat transfer becomes more efficient, from 40 to 1000 times that of a copper rod of the similar size. (Chi, 1976)

Heat pipes have several other advantages. They are much lighter than the solid metal conductors of the same size. In space applications, the light weight of a heat pipe becomes an advantage. Also, a heat pipe is essentially a self-contained, sealed unit that is maintenance-free and requires no external pump. Heat pipes can be used in a wide range of temperatures by selecting the proper working fluid, a cryogenic fluid for low temperature and liquid metal for high temperature applications. In addition, heat pipes can be fabricated into a variety of shapes and sizes.

The applications of heat pipes are varied and numerous. Some of their uses are thermal switches, thermal diodes, and thermal shields. For the Trans-Alaska Pipeline System, a maintenance-free heat transfer device was required to conduct heat away from the permafrost to protect the environment and to prevent the structure from sagging under the melting ice (Chi, 1976). Heat pipes became the best answer for this problem. Recently, Faghri, et al. (1989), developed gloves that use heat pipes to transfer heat from the elbow to the fingertips to prevent frost bite in an extremely cold environment. For their adaptability to different needs, low maintenance cost, and other advantages, heat pipes are being considered in a variety of applications which require a more efficient transfer of heat.

LITERATURE REVIEW

Heat Pipe Operation

The heat pipe typically is divided into three regions, evaporator, adiabatic, and condenser. Heat addition occurs in the evaporator and results in a temperature and pressure rise. In the adiabatic, no heat transfer with the surrounding occurs, and in the condenser, heat is rejected. The pressure rise in the evaporator as a result of the heat addition creates a pressure gradient along the length of the heat pipe. This pressure gradient drives the vapor flow from the evaporator to the condenser region where heat rejection results in the condensation of the vapor. The condensed liquid then returns to the evaporator by the capillary pumping force provided by the wick structure. Fig. 1 shows the diagram of a conventional heat pipe.

The capillary pressure difference in the heat pipe wick structure results from a difference in the capillary radius in the wick as shown in Fig. 2. In the evaporator, the vaporization of the working fluid results in the liquid meniscus receding into the wick structure. The capillary radius of the pores then decreases. At the condenser, the condensation process deposits more liquid at the interface, resulting in a larger capillary radius. The maximum capillary pressure difference is described by the following equation:

$$\Delta Pcm = \frac{2\sigma}{r_{cc}} - \frac{2\sigma}{r_{ce}} \qquad (1)$$

This difference in the capillary radius provides the pumping mechanism which returns the condensed liquid from the condenser to the evaporator.

Operating Limits

During the steady-state operation of the heat pipe, the heat transfer capacity can be limited by the occurrence of several different phenomena, four of which are the boiling limit, capillary limit, sonic limit, and the entrainment limit. Fig. 3 shows a plot of these limits as a function of temperature. At low rates of heat transfer, only the liquid at the liquid-vapor interface is vaporized. When heat transfer rate to the evaporator increases,

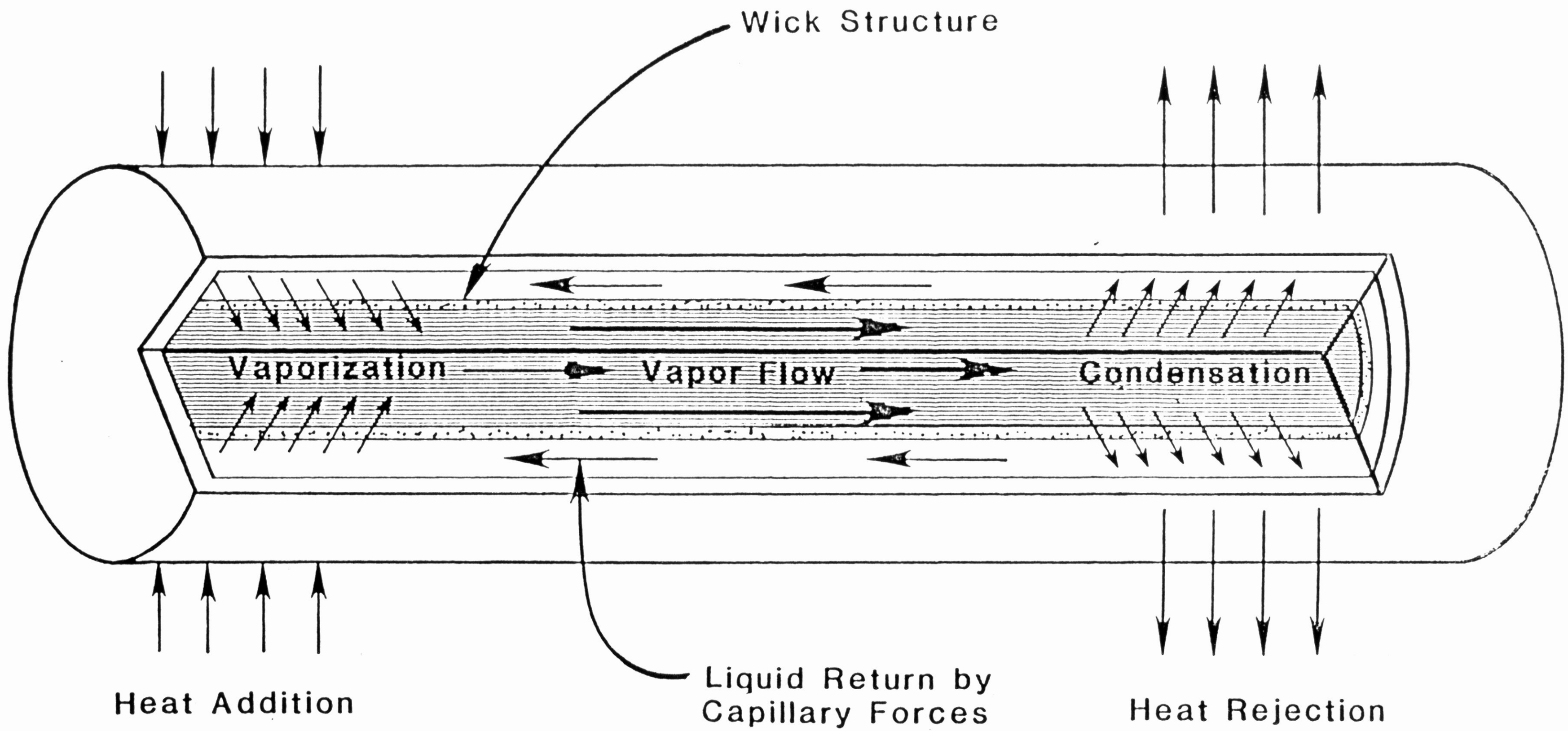


Fig. 1: Cross-Section of Conventional Heat Pipe

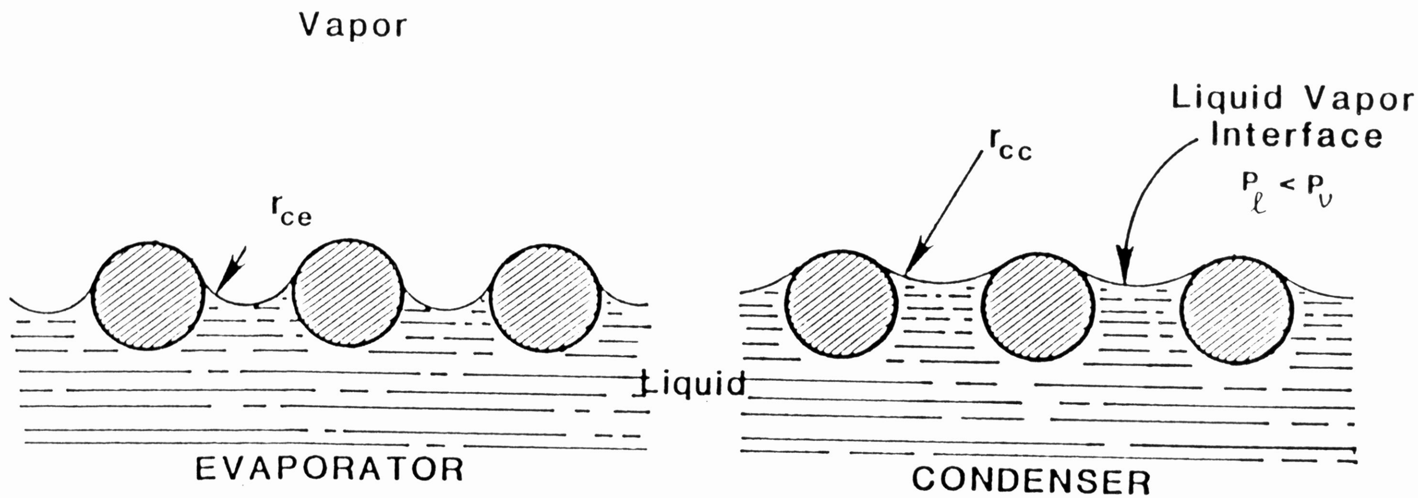
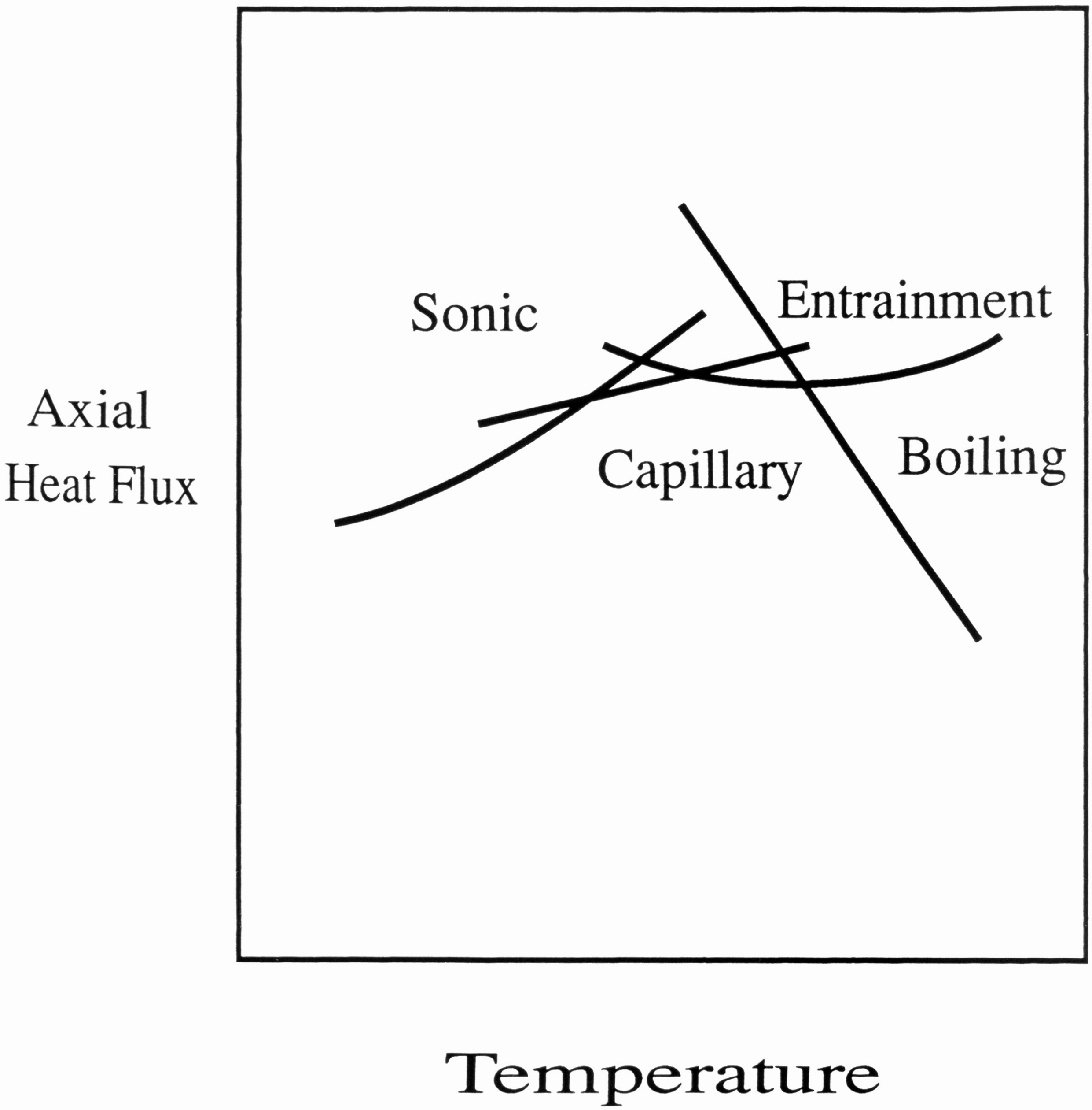


Fig. 2: Difference in Capillary Radii in the Condenser and the Evaporator

Fig. 3 Steady State Heat Transport Limits
as a Function of Temperature



boiling in the wick structure and in the liquid channel can occur. The bubbles in the wick and liquid channel impede the return of the liquid to the evaporator if the pore size of the wick structure is not large enough for the vapor to escape. The heat transfer rate at which boiling occurs in a heat pipe is defined as

$$Qmax = \frac{2 \Pi K_e L_e T_e}{h_{fg} \rho_v \ln (r_i / r_v)} \left(\frac{2 \sigma}{r_n} - \Delta P_{cm} \right) \qquad (2)$$

where r_n is the critical radius at which nucleation occurs and λ is equal to the wire diameter plus the wire spacing in the wick structure. The boiling limit, therefore, depends on the heat transfer rate to the evaporator, the wick structure, and the properties of the working fluid. As boiling continues, and the heat input is further increased, the liquid return may be completely blocked, resulting in the wick dry-out in the evaporator section.

The capillary limit refers to the inability of the wick structure to provide enough capillary pressure difference to pump the liquid from the condenser to the evaporator. During the normal operation of a horizontal heat pipe, the capillary pressure difference is equal to or greater than the total pressure due to friction in the vapor flow and liquid flow and the normal hydrostatic pressure drop. The axial hydrostatic pressure drop is negligible since no body force acts on the fluid. This capillary limit can therefore be expressed by the following equation:

$$\Delta P_c = \Delta P_{norm} + \Delta P_l + \Delta P_v \qquad (3)$$

The capillary limit varies with the physical dimensions of the heat pipe, such as the type of wick and pore size, the fluid properties, heat flux, as well as the operating temperature of the heat pipe.

At the sonic limit, the vapor flow approaches the speed of sound, resulting in the choking of the flow. Chi (1976) compared this phenomenon to the choking of flow in a converging-diverging nozzle. In a converging-diverging nozzle, increases in velocity are achieved by varying the cross-sectional area. The highest vapor velocity is therefore, at the smallest cross-sectional area in a converging-diverging nozzle. In a heat pipe, the variation in vapor velocity is caused by the rate of evaporation and condensation of the working fluid. The mass flow rate of the vapor and therefore the vapor velocity increases up to the end of the evaporator and remains constant in the adiabatic section. With condensation taking place and a lower temperature in the condenser, the mass flow rate decreases. If the condenser temperature is further decreased, the operating temperature of the heat pipe is suppressed until the vapor velocity reaches the sonic velocity and the flow is choked. Further increase in heat rejection does not eliminate the choked flow condition. The sonic limit is predicted by Busse (1973) to be

$$Q_s = 0.474\, A_v\, h_{fg}\, P_{v,e}{}^{1/2}\, \rho_{\,v,e}. \tag{4}$$

The sonic limit is the maximum possible heat transfer that can be achieved at a given operating temperature, wick structure, and working fluid.

The fourth operational limit on heat pipes is the entrainment limit. It is the least understood of the four operating limits and is the topic of this investigation. In a heat pipe, the flow of vapor opposes the flow of liquid. The two opposing flows create a shear force on the liquid at the vapor-liquid interface that is proportional to the difference between the vapor velocity and the liquid velocity. When the difference is large enough, the shear force overcomes the surface forces of the liquid and tears off liquid droplets, and the vapor flow carries the droplets to the condenser. The maximum heat flux at the entrainment limit is a function of the properties of the working fluid and the physical dimensions of the heat pipe. The next section discusses in more detail the phenomenon of entrainment and the analytical equations developed to predict the entrainment in heat pipes.

Entrainment Limit

The entrainment of liquid droplets in the vapor flow in a heat pipe as a heat transfer rate limiting mechanism has not been thoroughly investigated. The entrainment limit studies available to date yield four different equations for the maximum heat transfer rate of a heat pipe at the start of liquid droplet entrainment. The first equation was developed by Cotter (1967) and is derived with the assumption that at the onset of entrainment the Weber number is equal to 1. The Weber number is the ratio of the viscous shear force to the forces resulting from surface tension, or

$$We = \frac{2 r_{hw} \rho_v V_v^2}{\sigma} \tag{5}$$

The vapor velocity can be determined from the heat flux in this equation:

$$V_v = \frac{Q}{A_v \rho_v h_{fg}} \tag{6}$$

At entrainment, We = 1, and an expression for the heat flux at entrainment has the form

$$Q_{max} = A_v h_{fg} \left(\frac{\sigma \rho_v}{2 r_{wh}} \right)^{1/2} \tag{7}$$

this equation indicates that the entrainment limit in operating heat pipes is related to both the physical size of the heat pipe and properties of the working fluid.

Kemme (1976) modified Cotter's equation to include the effect of buoyancy on entrainment during vertical operation. He approximated the buoyancy effect by the term ρgD. The buoyancy term was derived from the Wallis (1969) criterion for flooding correlation for two-phase vertical flow. The modified equation for entrainment limit then becomes

$$Q_{max} = A_v \, h_{fg} \left(\frac{\rho_v}{A^*} \left(\frac{2 \sigma \pi}{\lambda} + \rho_l \, g \, D \right) \right)^{1/2} \tag{8}$$

where λ, the wavelength associated with the liquid surface, is defined as the wire diameter plus the distance between two wires in a mesh, and A^* is defined as a dimensionless constant equal to 2.2 for turbulent flow.

The third equation for predicting entrainment limit was developed by Prenger (1984) for textured wall, gravity assisted heat pipes. The textured wall partially protects the liquid flow from the vapor flow, therefore minimizing the effect of the vapor inertia on entrainment. The liquid inertia, therefore, became the dominant inertial effect, and the equation becomes

$$Q_{max} = 2 \, A_v \, h_{fg} \frac{D_{wire}}{D_{pipe}} \left(\frac{\rho_l \, \sigma}{\pi \, D_{pipe}} \right)^{1/2} \tag{9}$$

This equation included the effect of both the working fluid's properties and the physical dimensions of the heat pipe on the maximum heat flux at entrainment limit. Prenger also stated that rather than flooding, the depth of the liquid channel limits the heat flux at entrainment.

With the exception of Prenger's equation, the entrainment limit correlations developed thus far presume that the wick structure was flooded. In theory, though, the wick was not flooded in normal heat pipe operation. The fluid is retained in the wick structure and the shear force at the vapor-liquid interface must then overcome the energy required to tear the liquid droplets from the wick, not the energy needed to tear liquid droplets from the surface waves that formed above the wick structure. Rice and Fulford (1987) developed an equation for the entrainment limit based on these assumptions.

$$Q_{max} = h_{fg} \, A_v \left(\frac{8 \, \sigma \, \rho_v}{l} \right)^{0.5} \tag{10}$$

where l , the characteristic length of the wick, is twice the radius of curvature of the largest sustainable drop of working fluid in the pores of the wick. At the time of writing the paper, this equation had not been experimentally verified.

Similar to a study conducted by Bage and Peterson (1989), the theoretical maximum heat fluxes predicted by these four equations have been calculated for the heat pipe apparatus used in this investigation, with dimensions given in Table 1. The calculated entrainment limits were graphed in Fig. 4. This plot shows that a large discrepancy existed among the data obtained from the four equations. This large discrepancy indicated that the entrainment limit is not well understood, and therefore requires further in-depth studies.

Table 1: Dimensions of heat pipe apparatus for the calculation of theoretical heat flux at entrainment

Wire Diameter	0.023" (0.0584 cm)
Wire Spacing	0.105" (0.267 cm)
Vapor Passage Width	1.05" (2.67 cm)
Vapor Passage Height	0.32" (0.813 cm)

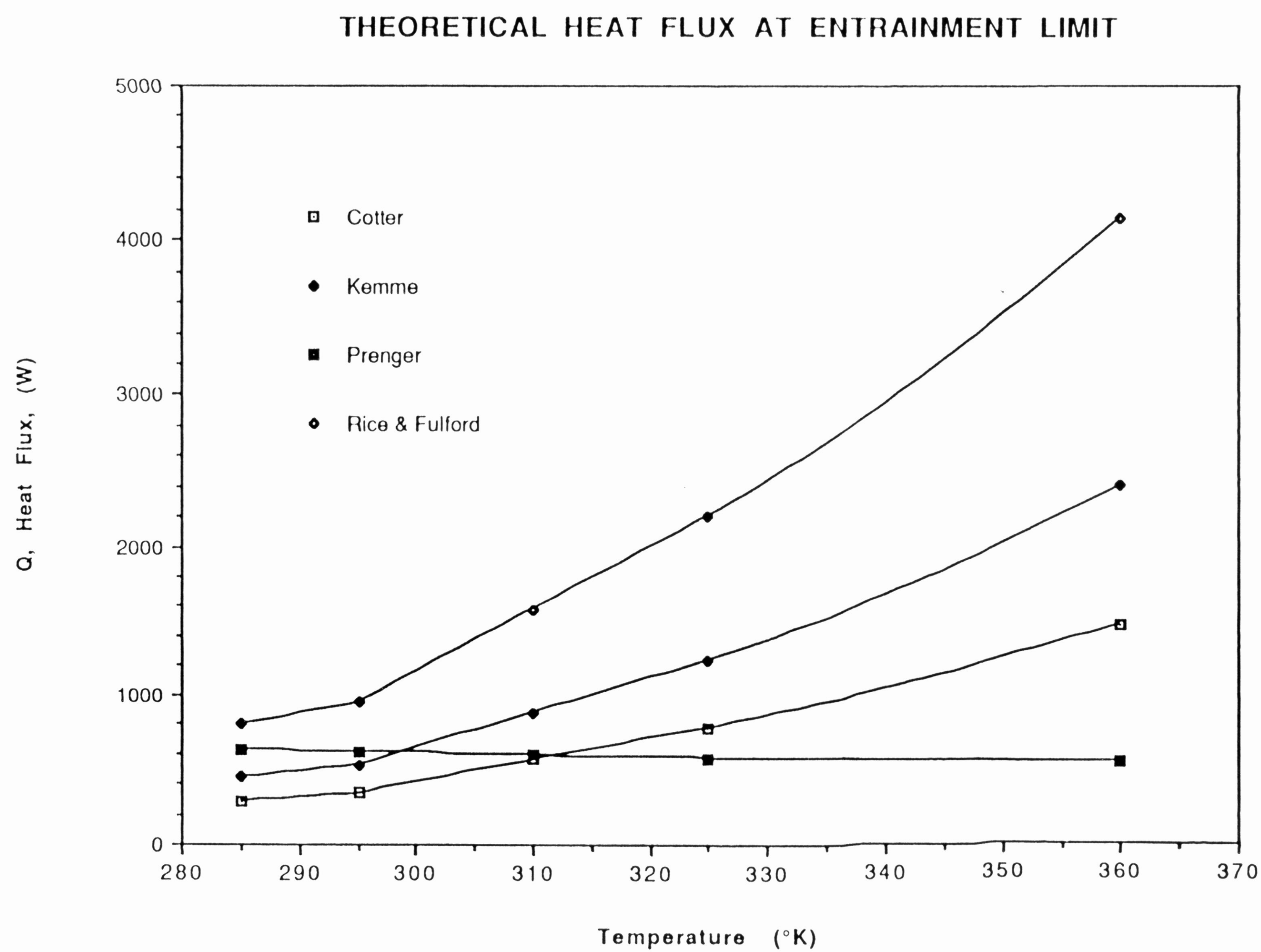


Fig. 4: Theoretical Maximum Heat Flux at the Entrainment Limit as a Function of the Operating Temperature

EXPERIMENTAL APPARATUS

The experimental apparatus used in this investigation is shown in Fig. 5 and consists of a rectangular heat pipe with a copper wire screen for the wick and water as the working fluid. The physical dimensions of the heat pipe were previously calculated (Lorenz, 1989) to ensure that the entrainment limit would be reached before reaching the other steady-state operational limits. One of the physical dimensions that influences the onset of entrainment is the vapor passage cross-sectional area. For a given power input, a smaller vapor passage area gives a higher vapor velocity (or higher mass flow rate), therefore creating a higher shear stress at the vapor-liquid interface. A 40-mesh copper wire screen, with a wire diameter of 0.023" and a hydraulic radius of 0.053", was selected for this investigation because of its large pore size or hydraulic radius. The coarseness of the 40-mesh translates into a weaker surface tension retaining the fluid in the wick, therefore decreasing the force required to tear liquid droplets from the wire screen.

The heat pipe had a clear Lexan top to facilitate a window through which entrainment could be monitored visually. Two different plate thicknesses--0.125", and 0.375"--were used to provide different vapor passage cross-sectional areas, therefore different vapor velocities. A greased O-ring provided the vacuum seal between the lid and the heat pipe. The assembly was then bolted together with an aluminum guide on top of the Lexan to help distribute the pressure more evenly. At the condenser end of the heat pipe, a hole was tapped in the wall and plugged with clear Lexan to provide an entrance window for a laser beam. The laser beam traveled through the window in the wall and down the length of the heat pipe. In a pure vapor flow, the laser beam was invisible. When entrainment occurred, the beam was reflected by entrained liquid droplets in the vapor stream. The laser used for this investigation was an Aerotech LSR12MR.

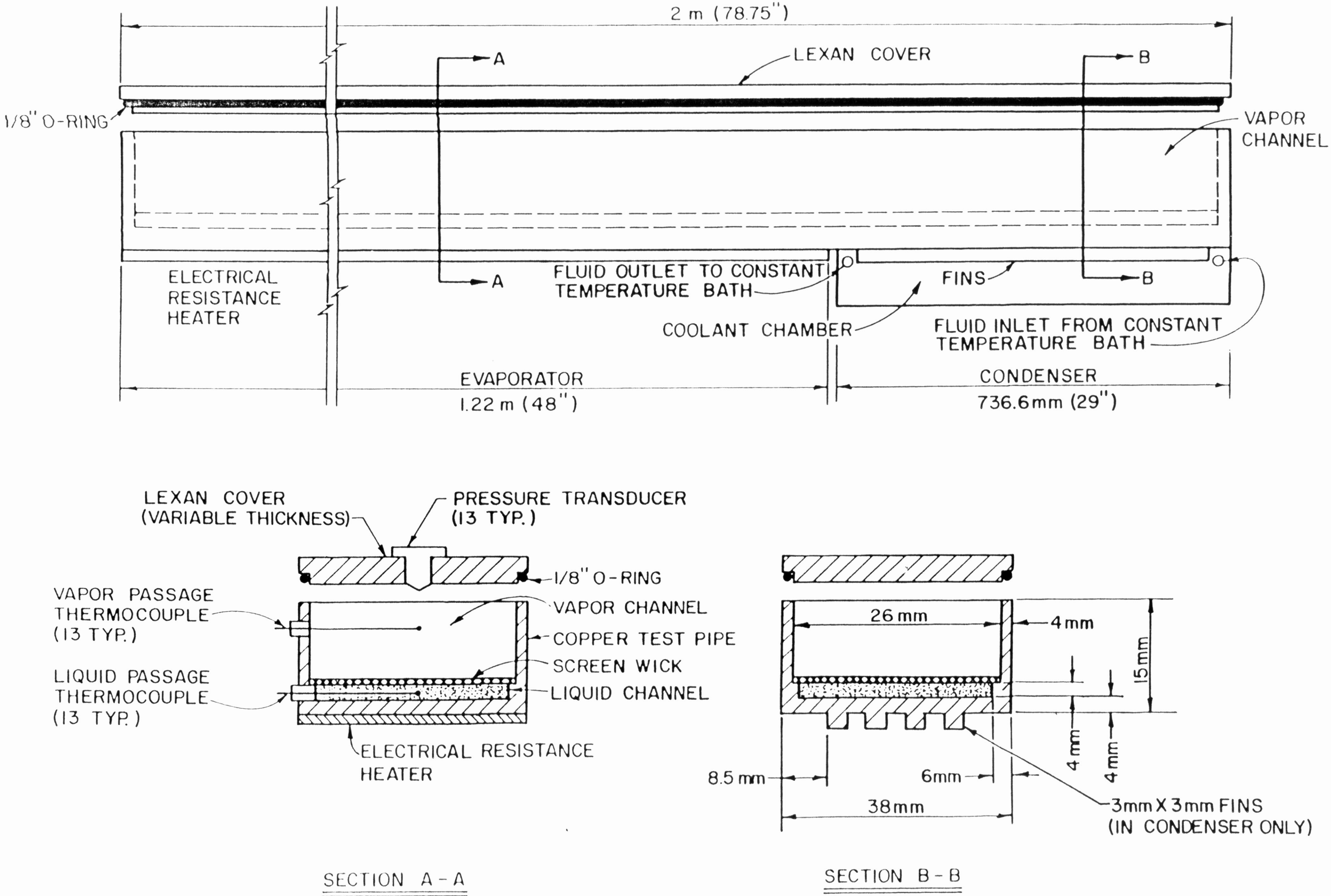


Fig. 5: Experimental Apparatus

Thermal power was provided by a variable transformer and was measured by a digital wattmeter. Electrical resistance heating using nichrome wires embedded in silicon rubber provided heat to the evaporator. The condenser section of the heat pipe was cooled by circulating a 50-50 mixture of freon and water through a Forma-Scientific constant temperature cooling bath and then through a separate channel along the bottom of the condenser section. By adjusting the evaporator power input and/or the temperature of the condenser, different operating temperatures, or different adiabatic vapor temperatures of the heat pipe were obtained.

The experimental facility also included a vacuum pump for evacuating the heat pipe prior to charging the pipe with pure distilled water. The vacuum pump used for this investigation was a Centorr model 14-3x8T-16.5.

Data acquisition for this investigation was automated because of the fast response of the heat pipe. To obtain a representative instantaneous temperature and pressure profile, the readings was recorded in succession and as quickly as possible. A BASIC program interfaces a Hewlett Packard Vectra 37A personal computer with a Hewlett Packard model 3497A data acquisition system. Twenty-six holes were tapped along the length of the heat pipe, with thirteen holes in the liquid channel and thirteen holes in the vapor channel. Twenty-six sheathed copper constantan thermocouples were then inserted, thirteen in the vapor channel and thirteen in the liquid channel. To map the axial pressure distribution, thirteen Omega Series PX236 pressure transducers were mounted on the Lexan cover. The BASIC program was designed to convert the voltages from the pressure transducers and the thermocouples into pressure and temperature values, respectively.

EXPERIMENTAL PROCEDURE

The procedure used in this investigation was designed to imitate the commercial procedure for manufacturing heat pipes.Before charging the heat pipe with distilled water, a vacuum was drawn inside the heat pipe. The vacuum achieved inside the heat pipe was 0.0 torr, with initial leakage rate of 0.5 torr/ 6 min. Next, the heat pipe was back-filled with the proper amount of water to flood the wick structure, accounting for the condensation on the Lexan cover.

After charging the heat pipe, the constant temperature bath was started, and cooling fluid was circulated through the channel below the condenser. When the condenser reached a constant temperature, heat was supplied to the evaporator at a constant power setting. From the temperature-time profile for a test run plotted in Fig. 6, the heat pipe temperature stabilized within 30 minutes after the heat source had been applied to the evaporator section. Therefore, in the experimental procedure, the heat pipe was allowed to run at each power level for 30 minutes. Because of the known vacuum leaks, the heat pipe was vented of any noncondensable gas at the end of the stabilization time. To allow the heat pipe to respond to the changes in the conditions, temperature and pressure profiles were obtained 30 seconds later. When entrainment was observed or when the power input exceeded the theoretical maximum heat flux predicted from Eq. (7) - (10), the power setting and/or the condenser temperature were adjusted to obtain a higher adiabatic temperature. When entrainment was not observed, the power input and the cooling bath temperature were adjusted to maintain the same adiabatic temperature. The procedure was repeated at several temperatures.

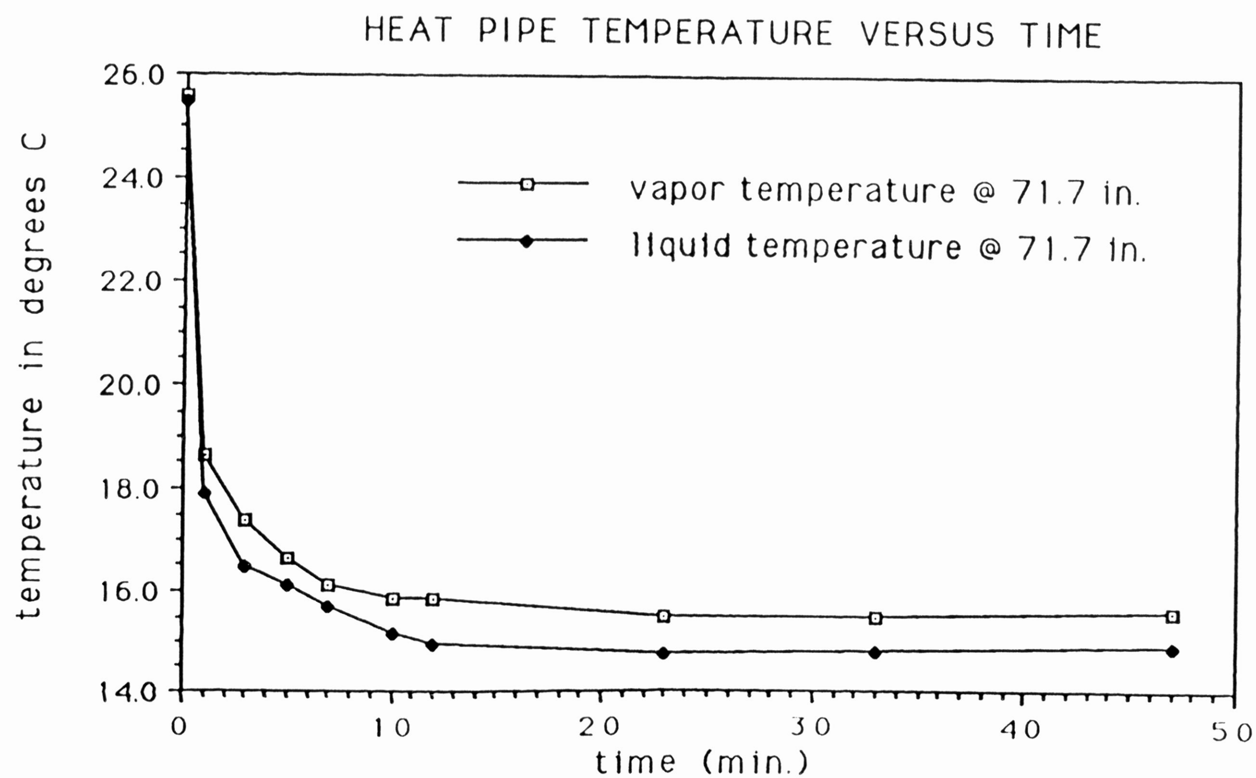


Fig. 6: Transient Temperature Response of a Selected Thermocouple

OBSERVATIONS

While operating the heat pipe, the behavior of the working fluid was carefully monitored to help understand the operating of this device. During Trial 1, when the power level was raised to 177 watts, boiling in the liquid channel and in the wick was observed. The non-uniform wall thickness where thermocouples had been tapped into the wall provided a favorable nucleation site for boiling to initiate. Both Trials 1 and 2 exhibited some boiling in the liquid channel and the wick.

Boiling in the wick resulted in the retardation of liquid flow back to the evaporator. At higher heat input, this process led to the dry-out of the wick structure in the evaporator and decreases the heat transfer efficiency of the heat pipe.

Another behavior observed during the operation of the heat pipe in both Trials 1 and 2 is the "slugging" of water at higher power inputs--177 watts for Trial 1 and 103 watts for Trial 2. Figure 8 shows graphically the development of liquid slugging. Vapor bubbles and flooding in the wick created and sustained pools of water above the wick structure. Due to the small vapor passage area, 0.32" in height, the condensation on the lid was periodically in contact with the water in the liquid channel and formed a slug or a wall of water which blocked the vapor passage. Eventually, the pressure difference between the evaporator side of the slug of water and the condenser side pushed the liquid to the condenser end, sweeping away the condensed liquid on the Lexan lid. This slugging effect was most prominent immediately after venting the heat pipe when the axial pressure gradient was increased as a result of venting. Up to 10 slugs for the first minute were recorded for the first trial and 5 slugs during the first minute for the second trial.

Finally, in Trial 2, the working fluid inside a major portion of the condenser solidified, for a -30° C cooling bath temperature and 156 watt power input. The only section which remained in the liquid state was the first four inches of the condenser, adjacent to the adiabatic region. The freezing of the working fluid in the condenser

SLUGGING

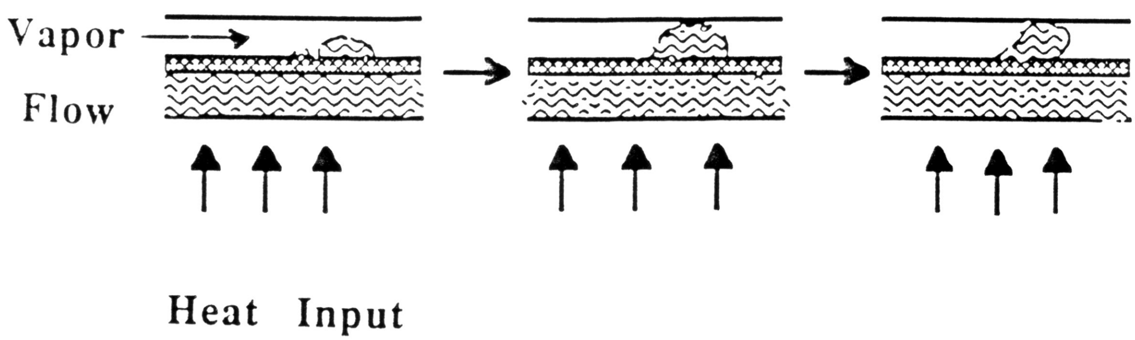


Fig. 7: Development of Liquid Slugging

probably resulted from the accumulation of noncondensable gas over the condenser region which prevented the transfer of heat by vapor flow to maintain some adiabatic or operating temperature despite the increased power input to the evaporator. However, the accumulation of noncondensable gas also kept the evaporator from drying out, after the working fluid in the condenser solidified. If the noncondensable gas had not been present, the liquid which condensed out of the vapor in the condenser region would also have frozen into ice. Eventually, the return of liquid could completely stop, resulting in a dry-out of the evaporator.

ANALYSIS OF RESULT

Noncondensable gases

Because of the known leakage, an effort was made during the operation of the heat pipe to track the increase in noncondensable gas inside the heat pipe. The presence of noncondensable gas in the condenser section of the heat pipe was manifested by the lack of condensation on the Lexan lid. During one trial, the noncondensable gas front was observed to move six inches in five minutes, increasing in the volume it occupied in the vapor space over the condenser region. Cracks in the Lexan lid contributed to the rapid deterioration of the vacuum inside the heat pipe. For this reason, the temperature profile at 30 seconds after venting the heat pipe was chosen to be more representative of the operating condition for the given power input, fluid, and condenser temperature.

Comparison with Analytical Results

Two sets of trials were conducted using the same vapor passage area and the same mesh size wire screen for the wick structure. The first set of trials, as plotted in Fig. 8 were completed by keeping the condenser temperature at 0° C. By increasing power input the operating temperature was thus increased. Higher heat fluxes could not be obtained, however, at the same operating temperature with the available power supply. Therefore, for the second set of trial runs, the condenser temperature was also adjusted to increase the heat flux without increasing the operating temperature of the heat pipe.

The thermocouples used for obtaining the temperature profile were designed for automated data acquisition systems. First, a reference voltage was recorded by the Hewlett Packard 3497 A data acquisition unit. The voltages corresponding to each thermocouple reading were then converted into temperatures in degrees Celsius using the reference voltage and other constants previously determined by the manufacturer. Manufacturer specifications indicated that the total accuracy for temperature readings with the Hewlett Packard 3497A was ±0.009°C/°C.

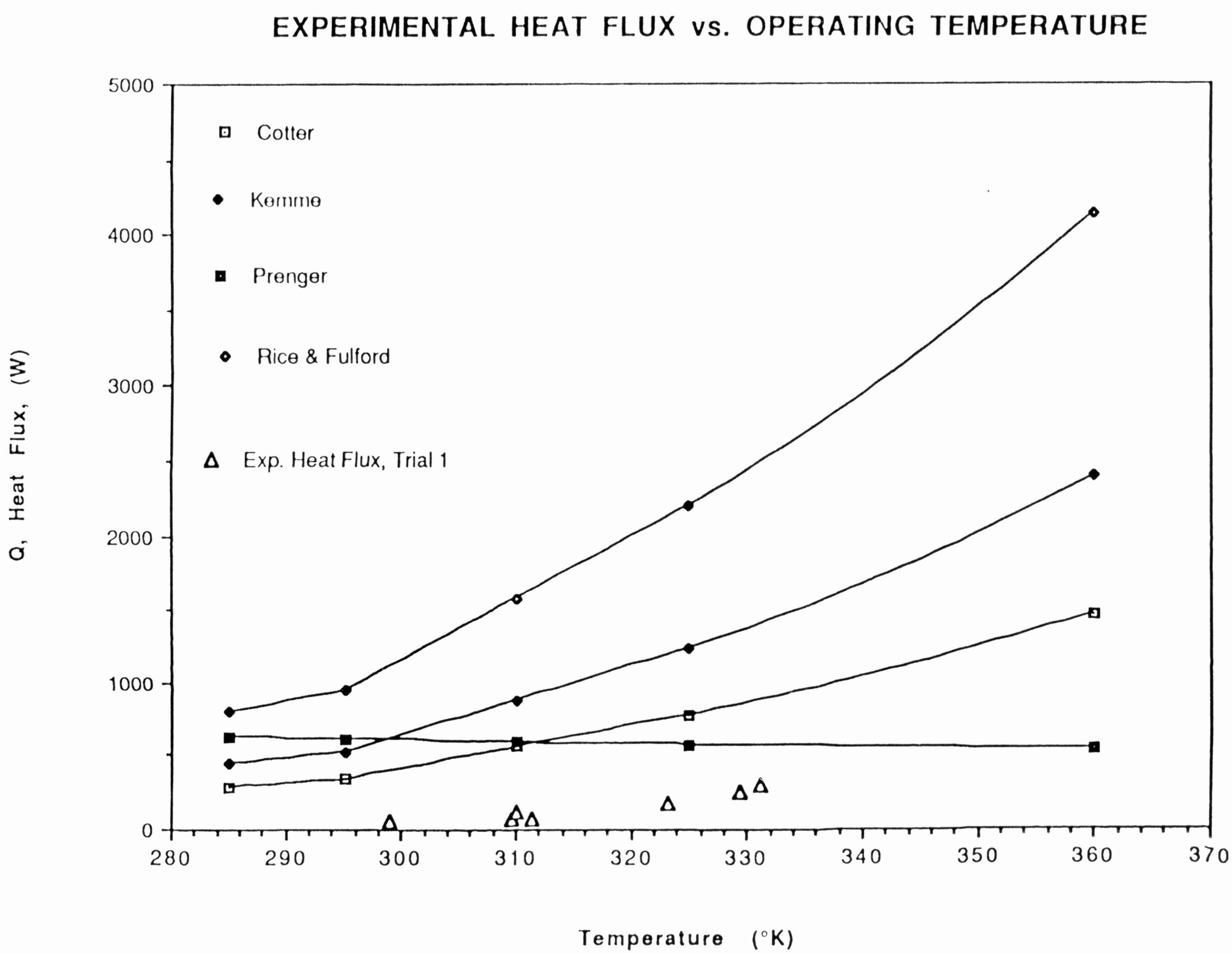


Fig. 8: Trial 1 Experimental Heat Flux vs. Operating Temperature Compared to Analytical Heat Flux at Entrainment Limit

Trial 1. Entrainment was not observed at any of the power levels tested. Therefore, the entrainment limit must be greater than the heat fluxes tested, or possibly at least as high as the entrainment limits predicted by Cotter and Prenger. It was discovered after the trials that the heat pipe was tilted slightly with the condenser above the evaporator, which provided gravity assistance in returning the condensed liquid back to the evaporator. The tilting of the heat pipe could have resulted in a higher heat flux at a given operating temperature because of the enhanced liquid return to the evaporator.

Trial 2. Fig. 9 plots experimental heat flux versus operating temperature for the various combinations of power input and condenser temperatures selected to maintain a relatively constant adiabatic temperature. For all combinations, entrainment was not observed. When superimposed on the analytical results, the plot indicates that the experimental heat flux at the selected adiabatic temperatures fell below the lowest values of heat flux at the entrainment limit as predicted by Cotter's and Prenger's equations. This graph thus indicates that the heat transfer at the entrainment limit must be higher than the experimental heat flux obtained at the adiabatic temperatures tested.

Trial 1 vs. Trial 2. The data obtained from the two sets of trials both indicate that the heat flux at the entrainment limit must be greater than the heat flux at the temperatures tested and may be as high as the heat fluxes predicted by the analytical equations. For the same condenser temperature, the operating temperature obtained for Trial 1 is lower than that of Trial 2. Three possible reasons could account for the discrepancies observed. The first possibility is the amount of noncondensable gas present in the heat pipe. The accumulation of noncondensable gas was more than likely different between the first trial and the second trial. In addition, liquid return to the evaporator was gravity assisted in the first trial, whereas for the second trial the liquid return was only facilitated by the capillary pumping force. Therefore, a higher heat transfer rate was achieved in the first trial than in the second trial at the same operating temperature. In other words, the operating temperature is lower in the first trial than in the second trial for a constant power input. The

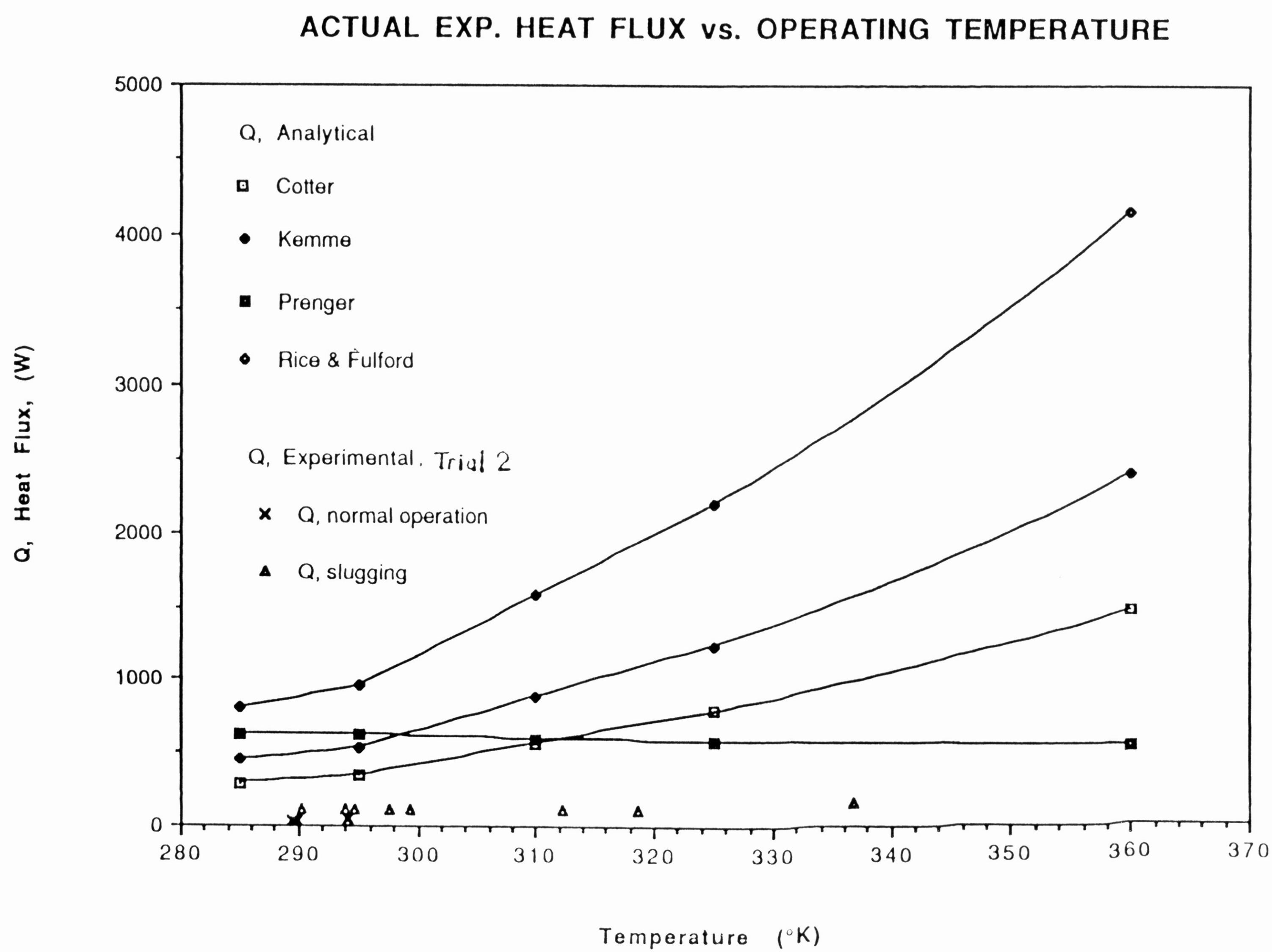


Fig. 9: Trial 2 Experimental Heat Flux vs. Operating Temperature Compared to Analytical Heat Flux at Entrainment Limit

main reason for the difference in results is the difference in the amount of compression of the O-ring. The O-ring provides the vacuum seal between the lid and the heat pipe. The more the O-ring is compressed, the smaller the vapor passage. One of the factors in predicting entrainment is the vapor passage area. The smaller the vapor passage area, the higher the velocity, and the faster entrainment will occur.

In Trial 1, the conditions of the experiment were not controlled well, therefore the data obtained may not be as representative of the operation of the heat pipe as the second trial.

Static vapor pressure profiles. An analysis of the vapor pressure profile was not possible due to the large uncertainty involved in the instrument and in the pressure measurement. The pressure transducers used to obtain the static vapor pressure profile were designed to measure gage pressure with a remote atmospheric pressure reference. These transducers were assumed to have a linear pressure-voltage relationship for the range of pressures concerned--from -14.7 psig to 30 psig. Each pressure transducer was calibrated at these two pressures. The slope and intercept values for each pressure were used to determine an equation for converting voltage readings to pressures. Manufacturer's specification indicated that the deviation for a 25 degree increase or decrease from room temperature (25°C) was ±3 mV. With a 10V dc voltage excitation, the typical voltage reading at -14.7 psig was 40 mV. At 0 psig, the voltage reading was typically 0 mV. The voltage/psi ratio was therefore approximately 2.72. The ±3 mV deviation translated into a pressure uncertainty of ±0.1 psi. A meaningful pressure profile, therefore, could not be obtained. A sample pressure profile has been included in the appendix.

CONCLUSION/RECOMMENDATIONS

An examination of the experimental data indicated the maximum heat flux may be as high as the minimum values predicted by the analytical equations, for heat pipes in which the wick structure has been flooded. Due to time constraints and troubleshooting, not enough data points were available to determine the actual entrainment.

Several of the steady-state operational behavior characteristics which were observed in this heat pipe included boiling, temporary wick dry-out, and slugging. The non-uniform thickness of the bottom wall provided nucleation sites for boiling to occur. A temporary wick dry-out was observed at high evaporator power input and probably was a result of boiling. Slugging was present also at power inputs as low as 103 watts for one set of trials. All three operational behaviors affected the efficiency of the heat pipe.

It is recommended that more tests be run to determine the actual entrainment limit. In conducting further experiments, more care should be taken in controlling the operating conditions. The compression of the O-ring must be carefully controlled, since a slight variation will change the vapor passage area of the heat pipe. Also, the procedure may need to be modified to vent the heat pipe more than once to withdraw the noncondensable gases more effectively.

The observed slugging affected the operation of the heat pipe. It was a behavior previously suspected in other heat pipes. Further analytical studies should be conducted to quantify the effect of slugging on heat pipe operation.

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APPENDIX

A. BASIC program for reading temperatures and pressures

B. Data sheets for Trial 1

C. Data sheets for Trial 2

D. Microsoft Excel spreadsheet for the calculation of theoretical heat flux at entrainment

E. Ideal plot of experimental heat flux versus operating temperature

F. Vapor temperature profile for varying power input and condenser temperature

A. BASIC program for reading temperatures and pressures

```
10 DATA 120,159,4  ! THESE ARE Tc LOCATIONS & RANGE
20 READ First_tc,Last_tc,N_readings
30 CLEAR 709
40 PRINTER IS 1
50 OUTPUT 709;"SA"    ! BEEP?
60 OUTPUT 709;"SD0"   ! TURN OFF DISPLAY FOR FASTER READING
70 DIM Temp(120:160,4),U(120:160,4),Tave(120:160),T_loc(120:160),Tsub(120:160)
80 DIM No_sec(1:10),B(1:14),Zer(1:14),Volt(1:14,4),Pave(1:13),Slope(1:14)
90 !DATA -40.079,-41.097,-39.595,-40.777,-39.11,-38.667,-38.577,-38.33,-38.371,-
38.772,-38.173,-38.446,-38.359
91 LINPUT "CALIBRATE PRESSURE TRANSDUCERS? (Y/N)",Cal$
92 IF Cal$="Y" OR Cal$="y" THEN GOTO 1680
93 ASSIGN @Path1 TO "IVAC"
100 FOR I=1 TO 14
110 ENTER @Path1;Zer(I)
130 NEXT I
131 LINPUT "READ VOLTAGE AT VACUUM? (Y/N)",Call$
132 IF Call$="Y" OR Call$="y" THEN GOTO 1680
140 !DATA .271,-.454,.376,-.374,-.329,.076,.099,.623,.457,.258,.631,.437,.475
141 ASSIGN @Path1 TO "IVOUT"
150 FOR I=1 TO 14
160 ENTER @Path1;B(I)
165 Slope(I)=(Zer(I)-B(I))/(-14.7)
170 NEXT I
180 R0=5.25792984E-7  ! SET UP CONSTANT VARIABLES FOR THERMOCOUPLE
190 R1=3.860071243E-5 ! TEMPERATURE CALCULATIONS
200 R2=4.186486602E-8
210 P0=.1238117795
220 P1=26861.17637
230 P2=-896494.288
240 P3=-46489260.88
250 P4=12441142450
260 P5=2.275304922E+12
270 P6=-6.399496867E+14
280 P7=5.435757807+16
290 P8=-2.02361537E+18
300 P9=2.830121167E+19
310 OUTPUT 709;"AC39"            ! READ IN REFERENCE VOLTAGE FOR THERMOCOUPLES
320 ENTER 709;R
330 !SETTING TIMED LOOP
340 PRINT "SETTING UP FOR TIMED DATA ACQUISITION..."
350 INPUT "ENTER THE COOLING BATH TEMPERATURE (IN DEGREES C) ",Bath
360 INPUT "ENTER THE MESH NUMBER ",Mesh
370 INPUT "ENTER THE POWER INPUT (IN WATTS) ",Watts
380 PRINT
390 INPUT "ENTER THE NUMBER OF TIMES TO TAKE DATA (<10)",No_run
400 FOR I=1 TO No_run
410 PRINT "NUMBER OF SECONDS DELAY BEFORE RECORDING TRIAL";I
420 PRINT "(number of seconds between successive trials)"
430 INPUT No_sec(I)
440 NEXT I
441 !
442 LINPUT "THE NAME OF THE DATA FILES WILL BEGIN WITH...?",Data$
450 ! Data$=CHR$(68)&CHR$(65)&CHR$(84)&CHR$(70)          !SETTING UP DATA FILES
460 Tc_wall=First_tc+9
470    T_loc(Tc_wall+2)=5.6875                    !CALCULATING THERMOCOUPLE
480    T_loc(Tc_wall+1)=6.1875                    !LOCATIONS IN INCHES FROM
490    Sub2=T_loc(Tc_wall+2)                      !THE EVAPORATOR END
500    Sub1=T_loc(Tc_wall+1)
510  REM CALCULATING LOCATIONS
```

```
520  FOR L=Tc_wall+3 TO Last_tc-2 STEP 2
530     T_loc(L)=6+Sub1
540     T_loc(L+1)=6+Sub2
550     Sub1=T_loc(L)
560     Sub2=T_loc(L+1)
570  NEXT L
580     T_loc(Last_tc-4)=77.1875
590     T_loc(Last_tc-5)=77.6875
600          T$=TIME$(TIMEDATE)
610         Start=TIMEDATE
620          D$=DATE$(TIMEDATE)
630  FOR M=1 TO No_run
631  CLEAR SCREEN
640  ON TIME (Start+No_sec(M)) MOD 86400 GOTO 690
650  PRINT TABXY(27,11),"PLEASE WAIT..."
660  PRINT TABXY(27,13),TIME$(TIMEDATE)
670  PRINT TABXY(27,15),TIME$(Start+No_sec(M))
680  GOTO 650
690  File_name$=Data$&CHR$(64+M)
710 FOR J=1 TO N_readings                ! READ IN THE VOLTAGES FROM ALL OF THE
720    FOR I=First_tc TO Last_tc         ! THERMOCOUPLES
730       OUTPUT 709;"AC";I
740       ENTER 709;U(I,J)
750    NEXT I
762 FOR I=0 TO 14                        ! READ IN VOLTAGES FROM PRESSURE
763    IF I=9 THEN GOTO 768              ! TRANSDUCERS
764    OUTPUT 709;"AC";I
765    ENTER 709;V
766    IF I<9 THEN Volt(I+1,J)=V*1000
767    IF I>9 THEN Volt(I,J)=V*1000
768    NEXT I
769    NEXT J
771 FOR J=1 TO N_readings                ! CONVERT THERMOCOUPLE VOLTAGES INTO
780    FOR I=First_tc TO Last_tc         ! TEMPERATURE IN DEGREES FARENHEIT
790       V0=R*10
800       V1=R0+V0*(R1+V0*R2)
810       V2=V1+U(I,J)
820       T1=P5+V2*(P6+V2*(P7+V2*(P8+V2*P9)))
830       T1=P0+V2*(P1+V2*(P2+V2*(P3+V2*(P4+V2*T1))))
840       T2=32+1.8*T1
850       Temp(I,J)=INT(T1*1000+.5)/1000
860    NEXT I
870 NEXT J
880 FOR L=First_tc TO Last_tc
890 Tsum=0
900 FOR K=1 TO N_readings                          !CALCULATING AVG TEMP
910   Tsum=Tsum+Temp(L,K)                          !TO 3 DECIMAL PLACES
920   NEXT K
930   Tsub(L)=INT(Tsum/N_readings*1000+.5)/1000
940 NEXT L
941 FOR L=1 TO 13                                  !CALCULATING AVG PRESSURES
942 Vsum=0
943 FOR K=1 TO N_readings
944 Vsum=Vsum+Volt(L,K)!+Volt(14,K)
945 NEXT K
946 Vave=Vsum/N_readings
947 Pave(L)=INT((Vave-B(L))/Slope(L)*10+.5)/10
948 NEXT L
950   FOR L=First_tc TO First_tc+9                 !MAPPING THERMOCOUPLES TO
960   Tave(L)=Tsub(L)                              !CHANNELS--1st 10 CHANNELS
```

```
970   NEXT L                                         !UNCHANGED
980   FOR L=First_tc+10 TO First_tc+17              !MAPPING THERMOCOUPLES TO
990   Tave(L+2)=Tsub(L)                             !CHANNELS--10th-18th CHANNELS
1000  NEXT L                                        !SHIFTED BY 2 POSITIONS
1010  F=First_tc
1020  FOR L=First_tc+20 TO First_tc+29            !MAPPING THERMOCOUPLES TO
1030  Tave(L+4)=Tsub(L)                           !CHANNELS--21st-30th CHANNELS
1040 NEXT L                                       !SHIFTED BY 4 POSITIONS
1050  Tave(F+10)=Tsub(F+30)                   !MAPPING THERMOUCOUPLES TO CHANNELS
1060  Tave(F+11)=Tsub(F+31)                   !ADDITIONAL ADJUSTMENTS
1070  Tave(F+20)=Tsub(F+34)
1080  Tave(F+21)=Tsub(F+35)
1090  Tave(F+22)=Tsub(F+32)
1100  Tave(F+23)=Tsub(F+33)
1110  Tave(F+34)=Tsub(F+36)
1120  Tave(F+35)=Tsub(F+37)
1130 OUTPUT 709;"SD1"              !  TURN DISPLAY BACK ON
1140 REM Print headings
1150 CLEAR SCREEN
1160 PRINTER IS 26
1170 PRINT TABXY(20,1),"DATASHEET FOR ENTRAINMENT IN HEAT PIPE"
1180 PRINT
1190 Dend$=DATE$(TIMEDATE)
1200 Tend$=TIME$(TIMEDATE)
1210 PRINT "RUN DATE:     ";Dend$
1220 PRINT "    TIME @ END OF RUN:   ";Tend$
1230 PRINT Bath;" DEGREES C CONSTANT TEMPERATURE BATH"
1240 PRINT "THE MESH NUMBER IS ";Mesh
1250 PRINT
1260 PRINT "THE POWER INPUT IS ";Watts;" WATTS"
1270 PRINT
1280 PRINT "TEMPERATURE READINGS ALONG THE HEAT PIPE WALL"
1290 PRINT "Location from the evaporator end"
1300 PRINT "TC #","in. ",TAB(29);
1310 PRINT "Avg Temp"
1320 REM AVERAGING TEMPERATURE READINGS
1330 Tc_wall=First_tc+9
1340 FOR L=First_tc TO Tc_wall
1350   Tc_loc=(L-First_tc+1)*4
1360   PRINT L,Tc_loc,TAB(29);
1370 PRINT Tave(L)
1380  NEXT L
1390 PRINT
1400 PRINT "LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE"
1410 PRINT "** locations are measured from the evaporator end **"
1420 PRINT
1430 PRINT "    VAPOR TEMPERATURE",TAB(46);"LIQUID TEMPERATURE"
1440 PRINT
1450 PRINT " TC #"," in. "," TEMP. ";TAB(42);" TC #"," in. "," TEMP."
1460 FOR L=Tc_wall+1 TO Last_tc-4 STEP 2
1470   PRINT L,T_loc(L),Tave(L),TAB(42);L+1,T_loc(L+1),Tave(L+1)
1480 PRINT
1490 NEXT L
1491 GOTO 1500
1493 PRINT "TC LOC.","PSIG."
1494 FOR L=First_tc+10 TO Last_tc-4 STEP 2
1495 PRINT (T_loc(L)+T_loc(L+1))/2,Pave((L-128)/2)
1496 NEXT L
1497 PRINTER IS 26
1500 CREATE File_name$,600
```

```
1510 ASSIGN @Path TO File_name$;FORMAT ON
1520    FOR L=First_tc+10 TO Last_tc-4             !OUTPUT TEMPERATURES
1530        OUTPUT @Path;VAL$(T_loc(L)),VAL$(Tave(L))
1540    NEXT L
1541    GOTO 1590
1550    FOR L=First_tc+10 TO Last_tc-4 STEP 2      !OUTPUT PRESSURE DATA
1560        Toc=(T_loc(L)+T_loc(L+1))/2
1570        OUTPUT @Path;VAL$(Toc),VAL$(Pave((L-128)/2))
1580    NEXT L
1590       OUTPUT @Path;VAL(Tend$)
1600       OUTPUT @Path;VAL$(Mesh);
1610      OUTPUT @Path;VAL$(Watts);
1620       OUTPUT @Path;VAL$(Bath);
1630      OUTPUT @Path;VAL(Dend$)
1640        ASSIGN @Path TO *
1650    PRINT "END OF PROGRAM"
1660 PRINTER IS 1
1665 OUTPUT 709;"SA"  ! BEEP?
1670    NEXT M
1680 END
```

Power input = 34 watts

[illegible].994
[illegible].559
38.554
34.728
33.698
30.424

[illegible] AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE

TC #	LO.	TEMP.
[illegible]	[illegible].1875	37.3[illegible]
[illegible]	12.1875	37.[illegible]
134	18.1875	36.684
136	24.1875	36.166
[illegible]	[illegible]0.1875	35.4[illegible]
[illegible]	[illegible].1875	32.6[illegible]
142	42.1875	28.31[illegible]
~~144~~	48.1875	24.446
146	54.1875	20.329
148	60.1875	17.937
150	66.1875	17.13
152	72.1875	15.58[illegible]
154	77.6875	15.61[illegible]

Adiabatic Temperature or Operating Temperature

LIQUID TEMPERATURE

TC #	LO.	TEMP.
[illegible]	[illegible].6875	[illegible]
[illegible]	11.6875	[illegible]
[illegible]	[illegible]7.6875	[illegible]
137	23.6875	[illegible]
[illegible]	29.6875	[illegible]
141	35.6875	[illegible]
143	41.6875	[illegible]
145	47.6875	25.[illegible]
147	53.6875	21.[illegible]
149	59.6875	18.[illegible]
151	65.6875	17.437
153	71.6875	16.[illegible]
1[illegible]5	77.1875	[illegible]

TC LOC.	PSIG.
5.[illegible]375	-13.5
11.[illegible]375	-13.4
17.[illegible]375	-13.5
2[illegible].[illegible]375	-13.3
[illegible]	-13.5
[illegible]	-[illegible].7
[illegible]	-[illegible].6
[illegible]	-[illegible]
[illegible]75	-[illegible]
[illegible]	[illegible]

RUN DATE: 11 Mar 1990
TIME @ END OF RUN: 20:37:21
0 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 47 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	41.578
121	8	42.101
122	12	42.101
123	16	42.771
124	20	41.22
125	24	41.179
126	28	43.63
127	32	31.061
128	36	37.486
129	40	33.488

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE

TC #	in.	TEMP.
130	6.1875	41.309
132	12.1875	41.19
134	18.1875	40.773
136	24.1875	40.223
138	30.1875	39.559
140	36.1875	35.975
142	42.1875	30.593
144	48.1875	25.815
146	54.1875	21.087
148	60.1875	18.471
150	66.1875	16.68
152	72.1875	15.442
154	77.6875	15.571

LIQUID TEMPERATURE

TC #	in.	TEMP.
131	5.6875	41.[illegible]
133	11.6875	41.3[illegible]
135	17.6875	41.447
137	23.6875	41.[illegible]
139	29.6875	40.[illegible]
141	35.6875	37.[illegible]
143	41.6875	31.994
145	47.6875	27.336
147	53.6875	22.105
149	59.6875	19.16
151	65.6875	17.178
153	71.6875	15.6[illegible]
155	77.1875	15.10[illegible]

TC LOC.	PSIG.
5.9375	-13.4
11.9375	-13.4
17.9375	-13.5
23.9375	-13.3
29.9375	-13.4
35.9375	-13.6
41.9375	-13.5
[illegible]	-13.7
[illegible]	-13.[illegible]
[illegible]	-13.[illegible]

[illegible] 11 Mar 19[illegible] [illegible]

[illegible]

[illegible]

TC #	in.	Avg Temp
120	4	46.[illegible]
121	8	47.2[illegible]
122	12	47.1[illegible]
123	16	38.0[illegible]
124	20	46.5[illegible]
125	24	46.576
126	28	49.[illegible]37
127	32	39.43
128	36	42.626
129	40	37.784

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	46.441	131	5.6875	47.[illegible]
132	12.1875	46.447	133	11.6875	47.[illegible]
134	18.1875	46.037	135	17.6875	46.[illegible]
136	24.1875	45.537	137	23.6875	47.5[illegible]
138	30.1875	44.943	139	29.6875	46.1[illegible]
140	36.1875	40.734	141	35.6875	42.[illegible]
142	42.1875	34.344	143	41.6875	36.[illegible]
144	48.1875	28.736	145	47.6875	30.58[illegible]
146	54.1875	23.1	147	53.6875	24.[illegible]
148	60.1875	19.864	149	59.6875	21.09
150	66.1875	19.356	151	65.6875	18.799
152	72.1875	16.417	153	71.6875	17.[illegible]
154	77.6875	16.301	155	77.1875	16.[illegible]

PC LOC.	PSIG.
5.9375	-13.1
11.9375	-13
17.9375	-13.1
23.9375	-12.9
29.9375	-13
35.9375	-13.2
41.9375	-13.[illegible]
47.9375	-13.[illegible]
[illegible]	-13.[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

RUN DATE: 11 Mar 1990 WATER 67 FA
TIME @ END OF RUN: 23:39:15
0 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 67 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	46.238
121	8	44.974
122	12	45.962
123	16	47.508
124	20	45.133
125	24	45.192
126	28	49.273
127	32	29.617
128	36	42.8
129	40	40.354

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	41.118	131	5.6875	41.745
132	12.1875	41.022	133	11.6875	41.624
134	18.1875	41.177	135	17.6875	41.905
136	24.1875	41.04	137	23.6875	40.709
138	30.1875	40.915	139	29.6875	41.939
140	36.1875	40.998	141	35.6875	41.463
142	42.1875	41.005	143	41.6875	39.737
144	48.1875	40.945	145	47.6875	37.46
146	54.1875	31.527	147	53.6875	29.572
148	60.1875	22.042	149	59.6875	22.162
150	66.1875	19.489	151	65.6875	19.65
152	72.1875	18.086	153	71.6875	18.22
154	77.6875	17.503	155	77.1875	17.606

[illegible] LOC.	PSIG.
5.9375	-14
11.9375	-13.9
17.9375	-14
23.9375	-13.8
29.9375	-13.8
35.9375	-14
41.9375	-13.9
47.9375	-14
[illegible]	[illegible]
[illegible]	[illegible]

RUN DATE: 11 Mar 1990

TIME @ END OF RUN: 23:47:22

0 DEGREES C CONSTANT TEMPERATURE BATH

THE MESH NUMBER IS 40

THE POWER INPUT IS 67 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL

Location from the evaporator end

TC #	in.	Avg Temp
120	4	42.972
121	8	43.517
122	12	43.652
123	16	45.168
124	20	43.528
125	24	44.373
126	28	49.145
127	32	29.623
128	36	43.859
129	40	41.986

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE

** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	42.806	131	5.6875	42.901
132	12.1875	42.675	133	11.6875	42.8
134	18.1875	42.723	135	17.6875	42.365
136	24.1875	42.658	137	23.6875	43.496
138	30.1875	42.8	139	29.6875	43.706
140	36.1875	42.77	141	35.6875	43.404
142	42.1875	42.806	143	41.6875	42.462
144	48.1875	36.609	145	47.6875	37.207
146	54.1875	25.645	147	53.6875	26.095
148	60.1875	20.686	149	59.6875	20.374
150	66.1875	19.245	151	65.6875	18.316
152	72.1875	18.508	153	71.6875	17.753
154	77.6875	13.616	155	77.1875	17.945

TC LOC.	PSIG.
5.9375	-13.9
11.9375	-13.8
17.9375	-13.9
23.9375	-13.7
29.9375	-13.7
35.9375	-14
41.9375	-13.8
47.9375	-14
53.9375	-14
59.9375	-13.8
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

[illegible]

[illegible] EVAPORATOR [illegible]

[illegible]	[illegible]	Avg Temp
[illegible]	4	[illegible]
[illegible]	9	[illegible]
[illegible]	10	[illegible]
[illegible]	14	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	13	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	41.6875	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	29.6875	[illegible]
[illegible]	[illegible]	54.[illegible]	151	65.6875	[illegible]
[illegible]	[illegible]	48.950	[illegible]	71.6875	[illegible]
[illegible]	[illegible]	45.114	155	77.1875	[illegible]

END OF PROGRAM

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	IN.	Avg Temp.
120	4	34.[illegible]
121	8	36.196
122	12	34.311
123	[illegible]	35.48
124	20	32.207
125	24	34.648
126	28	35.[illegible]99
127	32	32.254
128	36	30.053
129	[illegible]	26.104

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE

TC #	IN.	TEMP.
[illegible]	[illegible].1875	34.[illegible]
132	12.1875	34.653
134	18.1875	34.617
[illegible]	[illegible]	34.[illegible]
[illegible]	[illegible]	32.477
[illegible]	[illegible]	20.[illegible]
[illegible]	[illegible]	20.[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible].08
[illegible]	[illegible].1875	[illegible]
150	[illegible].1875	11.923
152	72.1875	11.17
154	77.6875	11.295

LIQUID TEMPERATURE

TC #	IN.	TEMP.
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible].6875	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible].6875	[illegible]
147	53.6875	[illegible]
[illegible]	59.6875	[illegible]
151	65.6875	[illegible]
[illegible]	71.6875	[illegible]
155	77.1875	[illegible]

TC LOC.	PSIG.
5.9375	777.1
11.9375	493
17.9375	277.5
[illegible].9375	276.2
[illegible]	254.6
[illegible]	[illegible]
41.9375	207.1
47.9375	83.3
53.9375	113.9

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	35.29[illegible]
121	8	35.309
122	12	35.497
123	16	35.909
124	20	36.116
125	24	34.919
126	28	36.357
127	32	33.567
128	36	32.455
129	40	29.297

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	35.[illegible]	131	5.6875	[illegible]
132	12.1875	34.456	[illegible]	[illegible]	[illegible]
134	18.1875	34.822	[illegible]	17.6875	[illegible]
136	24.1875	34.749	[illegible]	[illegible]	[illegible]
138	30.1875	[illegible]	[illegible]	[illegible]	[illegible]
140	36.1875	[illegible]	[illegible]	[illegible]	[illegible]
142	42.1875	25.[illegible]	[illegible]	[illegible]	[illegible]
144	48.1875	19.37[illegible]	[illegible]	[illegible]	[illegible]
146	54.1875	13.[illegible]49	147	53.6875	[illegible]
148	60.1875	11.01[illegible]	[illegible]	59.6875	[illegible]
150	66.1875	10.307	[illegible]	65.6875	[illegible]
152	72.1875	11.143	[illegible]	71.6875	[illegible]
154	77.6875	11.222	155	77.1875	[illegible]

TC LOC.	PSIG.
5.9375	785.4
11.9375	601.4
17.9375	487
23.9375	475.7
29.9375	457.7
35.9375	441.[illegible]
41.9375	404.[illegible]
47.9375	[illegible]
53.9375	274.3
59.9375	271.9
65.9375	289

[illegible]

THE POWER INPUT = 97 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	36.311
121	8	36.445
122	12	36.348
123	16	36.307
124	20	35.891
125	24	35.79
126	28	36.245
127	32	33.143
128	36	31.2
129	40	28.111

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	5.1875	36.263	131	[illegible]	[illegible]
132	12.1875	[illegible]	133	[illegible]	[illegible]
134	[illegible]	[illegible]	135	[illegible]	[illegible]
136	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
138	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
140	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
142	[illegible]	24.572	143	41.6875	[illegible]
144	48.1875	18.775	145	47.6875	[illegible]
146	54.1875	[illegible]	147	53.6875	[illegible]
148	[illegible]	[illegible]	149	59.6875	[illegible]
150	66.1875	10.131	151	65.6875	[illegible]
152	72.1875	11.29	153	71.6875	[illegible]
154	77.6875	11.479	155	77.1875	[illegible]

END OF PROGRAM

RUN DATE: 14 Mar 1990

TIME @ END OF RUN: 02:42:45

0 DEGREES C CONSTANT TEMPERATURE BATH

THE MESH NUMBER IS 40

THE POWER INPUT IS 50 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL

Location from the evaporator end

TC #	in.	Avg Temp
120	4	41.363
121	8	41.743
122	12	41.827
123	16	42.884
124	20	41.523
125	24	41.963
126	28	46.589
127	32	40.605
128	36	40.175
129	40	37.822

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE

** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	39.529	131	5.6875	40.802
132	12.1875	39.451	133	11.6875	40.133
134	18.1875	39.481	135	17.6875	40.337
136	24.1875	39.571	137	23.6875	41.361
138	30.1875	39.547	139	29.6875	39.87
140	36.1875	39.403	141	35.6875	38.448
142	42.1875	39.379	143	41.6875	34.96
144	48.1875	24.574	145	47.6875	24.863
146	54.1875	15.093	147	53.6875	15.666
148	60.1875	11.892	149	59.6875	12.243
150	66.1875	9.993	151	65.6875	10.535
152	72.1875	11.703	153	71.6875	10.221
154	77.6875	11.611	155	77.1875	10.[illegible]4

END OF PROGRAM

RUN DATE: [illegible]

[illegible]

TC #	in.	Avg. Temp.
120	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	45.115
[illegible]	[illegible]	45.755
[illegible]	[illegible]	44.345
[illegible]	[illegible]	43.402
[illegible]	[illegible]	47.141
[illegible]	32	42.562
[illegible]	[illegible]	42.734
[illegible]	40	42.449

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	38.429	131	5.6875	40.1[illegible]
132	12.1875	38.261	133	11.6875	40.234
134	18.1875	38.507	135	17.6875	39.377
136	24.1875	38.387	137	23.6875	41.[illegible]
138	30.1875	38.339	139	29.6875	39.515
140	36.1875	38.453	141	35.6875	39.537
142	42.1875	38.567	143	41.6875	38.662
144	48.1875	38.411	145	47.6875	35.943
146	54.1875	38.152	147	53.6875	30.603
148	60.1875	20.139	149	59.6875	20.4[illegible]
150	66.1875	13.725	151	65.6875	13.[illegible]
152	72.1875	12.685	153	71.6875	1[illegible]
154	77.6875	12.436	155	77.1875	11.[illegible]

END OF PROGRAM

RUN DATE: 14 Mar 1990

TIME @ END OF RUN: [illegible]

0 DEGREES C CONSTANT IS [illegible]

THE MESH NUMBER IS [illegible]

THE POWER INPUT IS [illegible]

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	44.[illegible]
121	8	45.[illegible]
122	12	44.[illegible]
123	16	50.[illegible]
124	20	42.[illegible]
125	24	4[illegible]
126	[illegible]	[illegible]
127	32	44.[illegible]
128	36	[illegible]
129	[illegible]	4[illegible].[illegible]22

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** Locations are measured from the evaporator end **

VAPOR TEMPERATURE

TC #	in.	TEMP.
[illegible]	[illegible].1875	37.229
[illegible]	12.1875	37.187
134	18.1875	37.44
136	24.1875	37.447
138	30.1875	37.513
140	36.1875	37.38
142	42.1875	37.29
144	48.1875	37.079
146	54.1875	36.945
148	60.1875	36.607
150	66.1875	37.313
152	72.1875	34.323
154	77.6875	17.736

LIQUID TEMPERATURE

TC #	in.	TEMP.
131	5.6875	39.[illegible]
133	11.6875	38.884
135	17.6875	38.5
137	23.6875	39.[illegible]
139	29.6875	39.[illegible]
141	35.6875	38.572
143	41.6875	37.8[illegible]
145	47.6875	36.7[illegible]
147	53.6875	35.225
149	59.6875	32.792
151	65.6875	30.418
153	71.6875	25.484
155	77.1875	17.0[illegible]

END OF PROGRAM

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 14 Mar 1990
TIME @ END OF RUN: 05:14:07
0 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 175 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	44.313
121	8	45.197
122	12	45.715
123	16	50.136
124	20	44.03
125	24	45.121
126	28	53.467
127	32	43.599
128	36	43.644
129	40	45.71

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	37.93	131	5.6875	39.504
132	12.1875	37.791	133	11.6875	39.[illegible]4
134	18.1875	38.117	135	17.6875	40.204
136	24.1875	37.894	137	23.6875	38.787
138	30.1875	37.918	139	29.6875	40.449
140	36.1875	37.966	141	35.6875	39.186
142	42.1875	37.912	143	41.6875	38.22
144	48.1875	38.014	145	47.6875	37.539
146	54.1875	37.707	147	53.6875	36.463
148	60.1875	37.707	149	59.6875	36.596
150	66.1875	38.146	151	65.6875	36.[illegible]21
152	72.1875	37.719	153	71.6875	34.[illegible]
154	77.6875	32.312	155	77.1875	32.[illegible]

END OF PROGRAM

[illegible] FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 14 Mar 1990
TIME @ END OF RUN: 07:22:21
0 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 177 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	53.524
121	8	54.016
122	12	54.743
123	16	59.429
124	20	52.595
125	24	53.208
126	28	62.461
127	32	33.997
128	36	52.065
129	40	46.971

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	45.903	131	5.6875	47.501
132	12.1875	46.055	133	11.6875	47.781
134	18.1875	46.014	135	17.6875	47.[illegible]
136	24.1875	45.873	137	23.6875	50.447
138	30.1875	45.996	139	29.6875	47.577
140	36.1875	45.797	141	35.6875	46.668
142	42.1875	45.92	143	41.6875	46.126
144	48.1875	45.914	145	47.6875	45.456
146	54.1875	45.738	147	53.6875	44.714
148	60.1875	45.556	149	59.6875	44.67
150	66.1875	46.333	151	65.6875	42.419
152	72.1875	44.513	153	71.6875	38.[illegible]
154	77.6875	30.036	155	77.1875	29.[illegible]

TC LOC.	PSIG.
5.9375	767.4
11.9375	563.4
17.9375	422.5
23.9375	311.7
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 14 Mar 1990
TIME @ END OF RUN: 08:47:22
0 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 177 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	54.677
121	8	56.164
122	12	56.346
123	16	60.907
124	20	54.163
125	24	55.761
126	28	64.905
127	32	34.938
128	36	54.718
129	40	55.619

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	49.839	131	5.6875	50.8
132	12.1875	49.572	133	11.6875	49.9[illegible]1
134	18.1875	49.572	135	17.6875	50.239
136	24.1875	49.543	137	23.6875	45.666
138	30.1875	49.688	139	29.6875	51.031
140	36.1875	49.792	141	35.6875	50.534
142	42.1875	49.943	143	41.6875	50.29
144	48.1875	49.624	145	47.6875	49.247
146	54.1875	49.438	147	53.6875	48.636
148	60.1875	49.287	149	59.6875	47.34
150	66.1875	49.846	151	65.6875	47.[illegible]
152	72.1875	49.09	153	71.6875	45.[illegible]
154	77.6875	40.769	155	77.1875	[illegible]

END OF PROGRAM

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 14 Mar 1990
TIME @ END OF RUN: 09:42:01
0 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 250 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	60.375
121	8	62.432
122	12	61.785
123	16	68.83
124	20	60.913
125	24	62.671
126	28	72.631
127	32	59.027
128	36	60.544
129	40	62.716

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	56.301	131	5.6875	57.271
132	12.1875	56.37	133	11.6875	57.066
134	18.1875	56.432	135	17.6875	57.056
136	24.1875	56.37	137	23.6875	57.455
138	30.1875	56.574	139	29.6875	57.498
140	36.1875	56.25	141	35.6875	56.817
142	42.1875	56.381	143	41.6875	56.506
144	48.1875	56.254	145	47.6875	55.396
146	54.1875	56.143	147	53.6875	55.026
148	60.1875	55.966	149	59.6875	55.0[illegible]
150	66.1875	56.909	151	65.6875	54.[illegible]
152	72.1875	53.90[illegible]	153	71.6875	51.[illegible]
154	77.6875	44.6[illegible]	155	77.1875	45.[illegible]

END OF PROGRAM

C. Data sheets for Trial 2

```
1541    GOTO 1590
1550    FOR L=First_tc+10 TO Last_tc-4 STEP 2       !OUTPUT PRESSURE DATA
1560        Toc=(T_loc(L)+T_loc(L+1))/2
1570        OUTPUT @Path;VAL$(Toc),VAL$(Pave((L-128)/2))
1580    NEXT L
1590       OUTPUT @Path;VAL(Tend$)
1600       OUTPUT @Path;VAL$(Mesh);
1610      OUTPUT @Path;VAL$(Watts);
1620       OUTPUT @Path;VAL$(Bath);
1630      OUTPUT @Path;VAL(Dend$)
1640        ASSIGN @Path TO *
1650    PRINT "END OF PROGRAM"
1660 PRINTER IS 1
1665 OUTPUT 709;"SA"  ! BEEP?
1670    NEXT M
1680 END
```

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 16:34:53
-1 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 25 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	30.977
121	8	30.995
122	12	30.786
123	16	30.78
124	20	29.639
125	24	28.208
126	28	28.704
127	32	25.623
128	36	24.156
129	40	22.253

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	30.774	131	5.6875	30.952
132	12.1875	30.256	133	11.6875	30.521
134	18.1875	29.515	135	17.6875	29.947
136	24.1875	28.14	137	23.6875	29.004
138	30.1875	25.954	139	29.6875	27.444
140	36.1875	23.565	141	35.6875	24.89
142	42.1875	20.429	143	41.6875	21.867
144	48.1875	16.397	145	47.6875	19.008

END OF PROGRAM
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 16:46:35
-1 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 25 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	31.541
121	8	31.535
122	12	31.319
123	16	32.121
124	20	30.309
125	24	29.952
126	28	31.006
127	32	28.281
128	36	26.521
129	40	24.882

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	31.406	131	5.6875	31.602
132	12.1875	30.938	133	11.6875	31.154
134	18.1875	30.39	135	17.6875	30.618
136	24.1875	29.52	137	23.6875	30.67
138	30.1875	28.046	139	29.6875	28.387
140	36.1875	25.202	141	35.6875	25.559
142	42.1875	20.884	143	41.6875	21.107
144	48.1875	14.778	145	47.6875	14.681
146	54.1875	8.275	147	53.6875	7.221
148	60.1875	7.406	149	59.6875	6.171
150	66.1875	9.914	151	65.6875	6.151
152	72.1875	7.847	153	71.6875	6.832
154	77.6875	8.866	155	77.1875	7.761

IPRESSURE	PROG	2	256	2772	24-Oct-89 10:47
IVOUT	ASCII	2	256	2774	2-Mar-90 23:06
NPRESSURE	PROG	4	256	2776	6-Nov-89 11:06
DATAM	HP-UX	768	1	2780	14-Feb-90 10:23
NT_T_VAX	PROG	20	256	2784	24-Jan-90 18:05
NT_T_TIMED	PROG	29	256	2804	14-Mar-90 12:29
LPRESSURE	PROG	4	256	2840	6-Nov-89 18:22
AJT4	PROG	18	256	2844	5-Mar-90 12:21
WUN	PROG	10	256	2863	16-Nov-89 15:10
WUNT	PROG	12	256	2873	11-Dec-89 15:56
WUNS	PROG	11	256	2885	30-Nov-89 10:01
AJT1	PROG	7	256	2896	12-Mar-90 23:58
TRIAL	PROG	23	256	2903	30-Jan-90 10:24
DATAN	HP-UX	768	1	2926	14-Feb-90 10:28
DATAO	HP-UX	768	1	2929	14-Feb-90 10:39
AJT5	PROG	17	256	2935	22-Mar-90 2:15
VOLT	PROG	2	256	3039	16-Jan-90 14:21
DATAD	HP-UX	768	1	3047	14-Feb-90 11:58
EXTRA_COPY	PROG	11	256	3203	26-Jan-90 17:42
DATAE	HP-UX	768	1	3214	14-Feb-90 12:04
DATDA	HP-UX	768	1	3217	17-Feb-90 10:13
DATBA	PROG	12	256	3220	11-Mar-90 12:29
TRANSIENT	HP-UX	2560	1	3232	10-Mar-90 19:50
DATBC	HP-UX	768	1	3245	14-Feb-90 15:31
DATBD	HP-UX	768	1	3248	14-Feb-90 15:37
DATBE	HP-UX	768	1	3251	14-Feb-90 15:42
DATCA	HP-UX	768	1	3254	14-Feb-90 15:58
DATCB	HP-UX	768	1	3257	14-Feb-90 16:02
DATCC	HP-UX	768	1	3260	14-Feb-90 16:06
DATCE	HP-UX	768	1	3263	14-Feb-90 16:13
DATCF	HP-UX	768	1	3266	14-Feb-90 16:18
DATCG	HP-UX	768	1	3269	14-Feb-90 18:02
DATCH	HP-UX	768	1	3272	14-Feb-90 18:06
DATDB	HP-UX	768	1	3275	17-Feb-90 10:18
DATDC	HP-UX	768	1	3278	17-Feb-90 10:23
DATDD	HP-UX	768	1	3281	17-Feb-90 10:27
DATDE	HP-UX	768	1	3284	17-Feb-90 10:33
DATFA	HP-UX	768	1	3287	17-Feb-90 15:42
DATFB	HP-UX	768	1	3290	17-Feb-90 15:46
DATFC	HP-UX	768	1	3293	17-Feb-90 15:50
DATFD	HP-UX	768	1	3296	17-Feb-90 15:54

NT_TRANS DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 14:06:33
-5 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	56.672
121	8	56.168
122	12	56.622
123	16	58.534
124	20	57.216
125	24	55.335
126	28	61.492

127	32	53.503
128	36	53.147
129	40	53.64

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	52.952	131	5.6875	53.675
132	12.1875	52.958	133	11.6875	54.212
134	18.1875	53.01	135	17.6875	53.52
136	24.1875	52.969	137	23.6875	55.531
138	30.1875	52.935	139	29.6875	53.119
140	36.1875	52.849	141	35.6875	51.49
142	42.1875	52.929	143	41.6875	48.413
144	48.1875	39.239	145	47.6875	35.909
146	54.1875	16.604	147	53.6875	13.483
148	60.1875	9.101	149	59.6875	7.971
150	66.1875	9.531	151	65.6875	6.031
152	72.1875	6.824	153	71.6875	5.978
154	77.6875	7.944	155	77.1875	6.586

END OF PROGRAM
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 14:09:23
-5 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	54.441
121	8	55.702
122	12	55.611
123	16	57.178
124	20	56.293
125	24	56.088
126	28	61.811
127	32	54.156
128	36	53.261
129	40	54.081

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 17:42:20
-5 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 52 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	41.02
121	8	41.491
122	12	41.182
123	16	42.086
124	20	40.967
125	24	40.375
126	28	41.646
127	32	36.148
128	36	33.814
129	40	31.5

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	41.044	131	5.6875	41.313
132	12.1875	40.752	133	11.6875	41.283
134	18.1875	40.376	135	17.6875	40.919
136	24.1875	39.4	137	23.6875	40.789
138	30.1875	37.64	139	29.6875	38.434
140	36.1875	34.15	141	35.6875	34.308
142	42.1875	29.194	143	41.6875	28.613
144	48.1875	21.128	145	47.6875	22.159
146	54.1875	12.227	147	53.6875	14.314
148	60.1875	9.557	149	59.6875	10.656
150	66.1875	10.335	151	65.6875	8.973
152	72.1875	6.782	153	71.6875	6.9
154	77.6875	6.901	155	77.1875	6.505

END OF PROGRAM
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 17:45:23

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 18:41:27
-10 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	51.7
121	8	51.937
122	12	52.932
123	16	55.499
124	20	52.748
125	24	53.052
126	28	58.536
127	32	50.32
128	36	50.36
129	40	52.138

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	46.077	131	5.6875	46.815
132	12.1875	45.989	133	11.6875	47.084
134	18.1875	46.035	135	17.6875	47.002
136	24.1875	46.112	137	23.6875	47.488
138	30.1875	46.235	139	29.6875	46.599
140	36.1875	45.859	141	35.6875	46.106
142	42.1875	45.748	143	41.6875	45.707
144	48.1875	45.56	145	47.6875	41.41
146	54.1875	45.29	147	53.6875	33.227
148	60.1875	26.512	149	59.6875	19.811
150	66.1875	12.42	151	65.6875	9.281
152	72.1875	4.304	153	71.6875	4.211
154	77.6875	4.643	155	77.1875	3.68

END OF PROGRAM
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 18:44:15

-15 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	61.497
121	8	62.846
122	12	62.479
123	16	63.589
124	20	62.846
125	24	61.335
126	28	65.168
127	32	54.612
128	36	50.681
129	40	46.865

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	62.128	131	5.6875	62.74
132	12.1875	62.128	133	11.6875	62.539
134	18.1875	61.86	135	17.6875	62.752
136	24.1875	60.445	137	23.6875	59.961
138	30.1875	56.695	139	29.6875	57.596
140	36.1875	49.133	141	35.6875	49.749
142	42.1875	36.863	143	41.6875	38.628
144	48.1875	20.971	145	47.6875	24.077
146	54.1875	4.831	147	53.6875	9.098
148	60.1875	.508	149	59.6875	1.967
150	66.1875	-2.479	151	65.6875	-1.848
152	72.1875	-.702	153	71.6875	-2.807
154	77.6875	.38	155	77.1875	-2.097

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 16:43:25
-15 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

END OF PROGRAM
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
-15 TIME @ END OF RUN: 20:40:22
~~-20~~ DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	62.032
121	8	62.912
122	12	62.572
123	16	64.476
124	20	63.334
125	24	63.056
126	28	67.514
127	32	57.555
128	36	53.507
129	40	49.214

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	62.305	131	5.6875	63.14
132	12.1875	62.478	133	11.6875	64.008
134	18.1875	62.578	135	17.6875	63.462
136	24.1875	61.876	137	23.6875	63.686
138	30.1875	58.904	139	29.6875	60.17
140	36.1875	51.2	141	35.6875	51.471
142	42.1875	38.338	143	41.6875	38.741
144	48.1875	21.755	145	47.6875	23.492
146	54.1875	4.996	147	53.6875	5.413
148	60.1875	1.933	149	59.6875	-.535
150	66.1875	.514	151	65.6875	-1.416
152	72.1875	1.311	153	71.6875	-.824
154	77.6875	2.547	155	77.1875	.42

END OF PROGRAM
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 23:06:59
-20 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	61.323
121	8	61.809
122	12	61.284
123	16	62.332
124	20	59.568
125	24	57.295
126	28	60.377
127	32	49.875
128	36	47.144
129	40	44.955

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	61.557	131	5.6875	62.154
132	12.1875	60.831	133	11.6875	64.02
134	18.1875	59.169	135	17.6875	59.546
136	24.1875	56.359	137	23.6875	58.419
138	30.1875	52.387	139	29.6875	52.427
140	36.1875	45.955	141	35.6875	46.183
142	42.1875	36.868	143	41.6875	38.122
144	48.1875	24.616	145	47.6875	26.524
146	54.1875	8.797	147	53.6875	10.322
148	60.1875	3.853	149	59.6875	5.121
150	66.1875	4.206	151	65.6875	2.46
152	72.1875	.372	153	71.6875	.526
154	77.6875	1.384	155	77.1875	.164

NEW20_103RA
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 23:17:48

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 22:46:57
-20 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 103 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	61.231
121	8	62.174
122	12	61.248
123	16	62.241
124	20	60.285
125	24	58.513
126	28	62.141
127	32	51.78
128	36	48.548
129	40	44.909

LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	61.533	131	5.6875	62.102
132	12.1875	60.8	133	11.6875	62.454
134	18.1875	59.915	135	17.6875	60.689
136	24.1875	58.237	137	23.6875	59.504
138	30.1875	55.612	139	29.6875	56.039
140	36.1875	49.6	141	35.6875	49.403
142	42.1875	38.799	143	41.6875	40.236
144	48.1875	26.396	145	47.6875	28.709
146	54.1875	11.189	147	53.6875	15.658
148	60.1875	5.225	149	59.6875	9.178
150	66.1875	4.682	151	65.6875	6.534
152	72.1875	1.348	153	71.6875	3.031
154	77.6875	2.251	155	77.1875	.765

END OF PROGRAM
DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 24 Mar 1990
TIME @ END OF RUN: 22:49:45

DATASHEET FOR ENTRAINMENT IN HEAT PIPE

RUN DATE: 25 Mar 1990
TIME @ END OF RUN: 00:54:14
-20 DEGREES C CONSTANT TEMPERATURE BATH
THE MESH NUMBER IS 40

THE POWER INPUT IS 156 WATTS

TEMPERATURE READINGS ALONG THE HEAT PIPE WALL
Location from the evaporator end

TC #	in.	Avg Temp
120	4	74.286
121	8	74.073
122	12	74.751
123	16	77.98
124	20	75.423
125	24	75.395
126	28	82.868
127	32	70.316
128	36	69.961
129	40	71.763

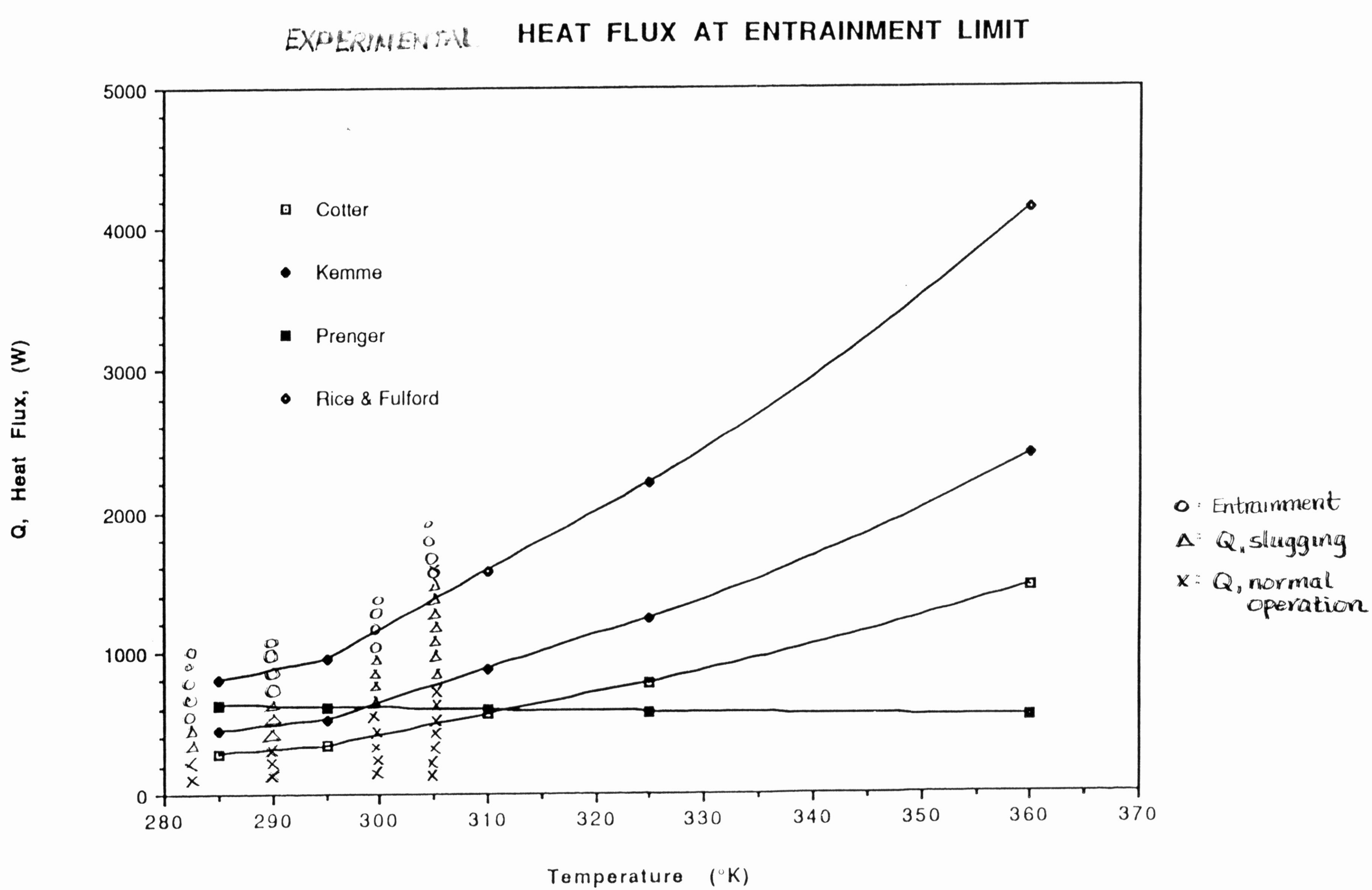
LIQUID AND VAPOR TEMPERATURES ALONG THE HEAT PIPE
** locations are measured from the evaporator end **

VAPOR TEMPERATURE			LIQUID TEMPERATURE		
TC #	in.	TEMP.	TC #	in.	TEMP.
130	6.1875	71.039	131	5.6875	71.142
132	12.1875	71.05	133	11.6875	72.915
134	18.1875	71.056	135	17.6875	71.239
136	24.1875	71.083	137	23.6875	71.596
138	30.1875	71.158	139	29.6875	71.121
140	36.1875	70.996	141	35.6875	67.517
142	42.1875	71.001	143	41.6875	61.103
144	48.1875	63.72	145	47.6875	40.048
146	54.1875	23.085	147	53.6875	12.793
148	60.1875	5.145	149	59.6875	-1.169
150	66.1875	.391	151	65.6875	-1.58
152	72.1875	1.255	153	71.6875	-1.776
154	77.6875	-.927	155	77.1875	-2.532

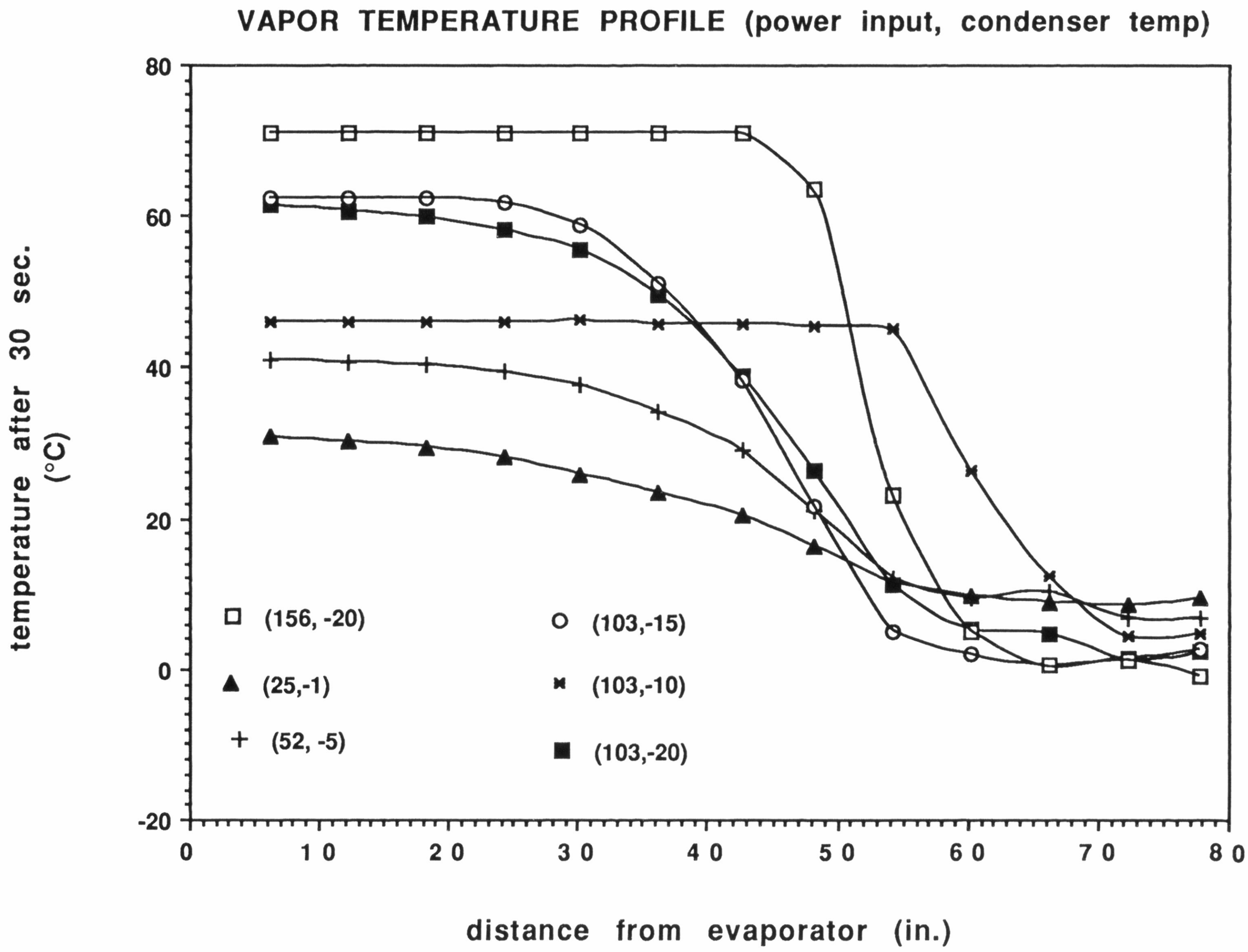
:CS80, 1500, 2
VOLUME LABEL: HPW_C
FILE NAME PRO TYPE REC/FILE BYTE/REC ADDRESS DATE TIME

D. Microsoft Excel spreadsheet for the calculation of theoretical heat flux at entrainment

	A	B	C	D	E	F
1	Properties of water					
2						
3	Temperature	Density, liq	Density, Vap	h, fg	Surface Tension	
4	°K	kg/m^3	kg/m^3	J/kg	N/m^2	
5	285	1000	0.010	2473000	0.0743	
6	295	1002	0.014	2461000	0.0737	
7	310	1007	0.044	2414000	0.0700	
8	325	1013	0.090	2378000	0.0675	
9	360	1034	0.378	2291000	0.0614	
10						
11						
12						
13	Height(m)	0.008128				
14	Width(m)	0.0267				
15	A, vapor(m)	0.0002				
16	r, wh	0.0013				
17	g	9.8100				
18	A *	2.2000				
19	l, char. leng	0.0054				
20	D, wire	0.0001				
21	D, pipe	0.0062				
22						
23	Calculated heat flux at entrainment limit					
24						
25	Temperature	Cotter's	Kemme	Prenger	Rice, Fulford	
26						
27	285	283.805	440.549	619.531	802.723	
28	295	335.911	522.527	614.644	950.100	
29	310	559.860	881.361	589.041	1583.523	
30	325	779.797	1238.951	571.496	2205.598	
31	360	1465.182	2389.695	530.535	4144.161	



E. Ideal plot of experimental heat flux versus operating temperature
(Expected results)



F. Vapor temperature profile for varying power input and condenser temperature