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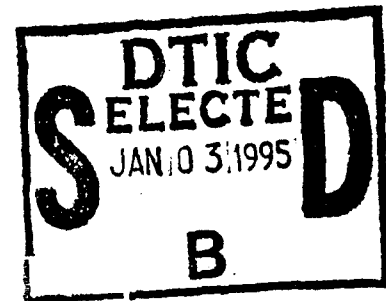
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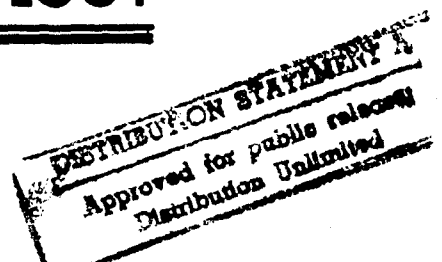
EXPERIMENTAL INVESTIGATION OF THE  
EFFECTS OF RELATIVE PHYSICAL  
ORIENTATION BETWEEN EVAPORATOR  
AND CONDENSER FOR A LOOP HEAT PIPE

THESIS

Brad R. Thompson, Captain, USAF

DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY  
**AIR FORCE INSTITUTE OF TECHNOLOGY**

Wright-Patterson Air Force Base, Ohio



AFIT/GA/ENY/94D-10

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CONDENSER FOR A LOOP HEAT PIPE

THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology  
Air University  
In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Astronautical Engineering

Brad R. Thompson, B.S.E.

Captain, USAF

December 1994

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## Preface

Heat pipes have been an area of interest to me long before I took my first class in Thermodynamics, where I started to gain an appreciation for how they work. This Thesis has provided me a chance to work with the latest developments in heat pipe technology, the loop heat pipe. I have enjoyed the opportunity to put one of these new devices to the test. Hopefully, the results found here will provide useful information for the future designers of these new devices.

There have been several people who have helped make this research possible. First I would like to thank Lt Col Bowman, my thesis advisor, for encouraging me to pursue an area of interest and pointing me to the people who could make things happen. This brings me to Dr. Jerry Beam, whom I would like to thank for allowing me the opportunity to work in the lab he oversees and for entrusting me with one of the few Russian heat pipes in the United States. Additionally, I would like to thank Don Reinmuller, John Leland, John Tennant, and Don Brightner for the day to day assistance they provided me in getting the pipe instrumented and the test equipment up and running. A special note of thanks is due to Gary Grogg who assisted me during much of the actual testing.

Finally, I want to thank my wife [REDACTED] and sons [REDACTED] and [REDACTED] for the love and support they have shown me throughout this effort.

Brad R. Thompson

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## ABSTRACT

This research examined the effects on performance of varying angular orientation and height differences between evaporator and condenser for a loop heat pipe. Performance was defined as the difference in temperature between evaporator and condenser ( $\Delta T$ ). The pipe was evaluated at varying input power ( $Q_{in}$ ) for: varying evaporator and condenser angles, different coolant temperatures, and varying relative height differences. All analysis included only steady state operation. The performance was influenced by condenser angles, with an optimal condenser angle for best performance being +45 degrees from horizontal. Additionally, the evaporator angles were found to influence performance only at low  $Q_{in}$  and low coolant temperatures. For high  $Q_{in}$ , performance was independent of evaporator angle. For small  $Q_{in}$  the  $\Delta T$  increased (poorer performance) with decreasing coolant temperature. However, for high  $Q_{in}$  the  $\Delta T$  was independent of coolant temperature. For small  $Q_{in}$ , the  $\Delta T$  increased with increasing heights of evaporator over condenser. However, for high  $Q_{in}$  the  $\Delta T$  was independent of the height difference. Additionally, pipe operation was sensitive to the rate of decrease of  $Q_{in}$ . Finally, an unexplained anomaly shows the pipe to operate at two different  $\Delta T$  values for a given heat input.

# **EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF RELATIVE PHYSICAL ORIENTATION BETWEEN EVAPORATOR AND CONDENSER FOR A LOOP HEAT PIPE**

## **I. Introduction**

### **A. Thesis**

This research experimentally investigates the effects on performance of relative physical orientations of the evaporator and condenser of a loop heat pipe (LHP). Relative physical orientations include angular displacements of the evaporator and condenser, and height differences between evaporator and condenser. The research objectives are: to map the performance of a loop heat pipe for relative evaporator and condenser elevations at varying relative angular orientations within a gravity field and; to determine possible failure modes of a loop heat pipe.

### **B. Background**

A loop heat pipe is a heat transfer device which takes advantage of the heat of vaporization of a working fluid to generate vapor pressure to pump the working fluid. A loop heat pipe operates much the same as a standard heat pipe except that it is a pressure driven device instead of a capillary driven device (see Figure 1.1). A loop heat pipe has an evaporator end into which heat is input, vaporizing a working fluid. The vapor is then transferred to the opposite end of the pipe to the condenser, where heat is removed. The

vapor then condenses to a liquid which is returned to the evaporator section and the process continued.

The evaporator consists of a porous wick structure which uses capillary force to draw and deliver liquid to a surface which is exposed to a heat source. At the heat absorbing surface of the wick, there are integrated passage ways (point 8 of Figure 1.1) which allow vapor to be communicated to an exhaust port in the shell of the evaporator (point 2 of Figure 1.1). The vapor then passes through a vapor line to the condenser section. The condenser section is in communication with a heat sink where the vapor releases its thermal energy and condenses back to a liquid (point 4 of Figure 1.1). The liquid is then transported back to the evaporator through a liquid return line (point 5 of Figure 1.1). The liquid is forced through the liquid line to the wick in the evaporator by the vapor pressure (point 6 of Figure 1.1), where it can be drawn again through the wick.

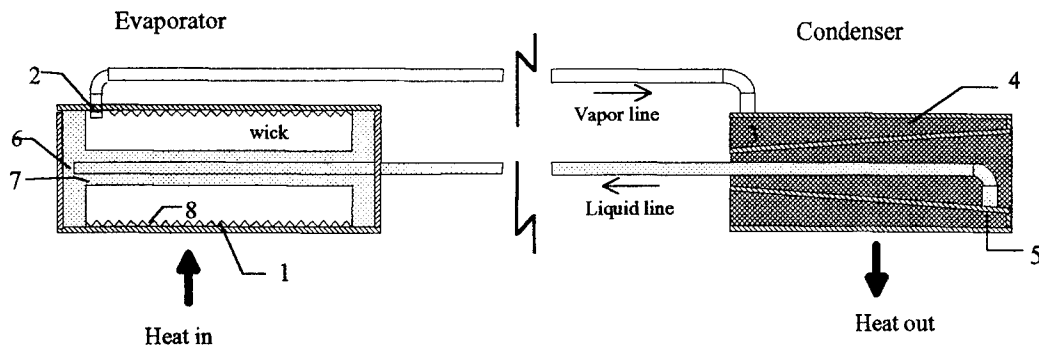


Figure 1.1 Loop Heat Pipe (Maidanik et al., 1985)

A more detailed explanation of the operation of a loop heat pipe is provided in Appendix A, and by Maidanik et al. in their US Patent Number 4,515,209.

The original loop heat pipe concept was invented in 1966 by American, F. J. Stenger (Maidanik, 1991). Recent developments in loop heat pipe technology have been accomplished almost exclusively in what was formerly known as the Soviet Union, with little expertise or knowledge of these devices within the United States Department of Defense (Beam, 1994). The loop heat pipe considered in the current study is of Soviet origin in both its design and manufacture.

Recent experimental research has examined the steady and transient operating characteristics of loop heat pipes with respect to gravity, that is, the LHP with the evaporator placed above the condenser (Dickey and Peterson, 1994; Meyer et al., 1993). A loop heat pipe, practically the same as that proposed here, was evaluated by Dickey and Peterson. The loop heat pipe they tested was made of stainless steel and was approximately three meters long with vapor and liquid lines of 4 mm and 3 mm outside diameter, respectively. The working fluid for their heat pipe was ammonia. Ammonia is the working fluid used in the current study. Dickey and Peterson positioned the evaporator at various heights above the condenser. However, the orientation of both the evaporator and condenser was allowed to rotate with the tilt angle of the pipe. No consideration was given to the relative angular orientation with respect to gravity, or angular orientation between evaporator and condenser. Dickey and Peterson's loop heat pipe was found to operate as long as the evaporator was less than 25.4 centimeters above the condenser. However, above 25.4 centimeters of relative height difference of evaporator over condenser, the loop heat pipe failed to start. Once the loop heat pipe was



operating, the relative height difference could be increased up to 61 centimeters before system failure.

To date, Dickey and Peterson have been the only ones to present an analytical model for loop heat pipe performance. Their model has low fidelity in that it only considers bulk temperatures of the liquid and vapor and the mass flow rates and makes no provisions for internal geometries. It is also restricted to only horizontal configurations (Dickey and Peterson, 1994). This horizontal restriction does not allow for the application of the model to the various angular orientations of the heat pipe tested here.

An additional loop heat pipe configuration has been evaluated by Meyer et al. The construction of their pipe is considerably different from the heat pipe tested in this effort. The performance of the Meyer et al. loop heat pipe was evaluated for different angular orientations with respect to gravity, but not for relative angular orientations between evaporator and condenser.

### **C. Justification**

Loop heat pipes are being increasingly considered for thermal control applications in aircraft and spacecraft. To insure adequate design of the thermal control system for the aircraft or spacecraft it is important to understand the performance of a given heat pipe design. Additionally, it must be understood what the potential failure modes are, or the conditions under which performance degradation can be expected.

Due to the physical layout of the loop heat pipe to be tested, there was a question as to how it would perform at certain angular orientations. It was suspected the heat pipe

would not perform when the condenser was oriented such that the inlet to the liquid return line was in the vertical direction (see Figure 1.1). Due to this construction, it was believed that at certain angular orientations, the performance of the loop heat pipe would begin to degrade. As mentioned in the research objectives, it is desired to determine what those limited performance orientations are and to quantify any performance degradation.

As part of the purchase of the given loop heat pipe by Wright Laboratory, Thermacore, the facilitator, provided initial test data. The data showed that testing was accomplished for various angular orientations and relative heights between the evaporator and condenser. The data indicates there is performance degradation, however, the data is insufficient to quantify the extent of this degradation (Russian Loop Heat Pipe, 1992). The test set-up used to gather the data was done as a quick preliminary look. No attempt was made to control extraneous environmental influences on the LHP performance, i.e. the heater input to the evaporator was uninsulated, thus the amount of energy input to the pipe was unknown.

In summary, little experimental or analytical work has been done on the effects of relative angular orientations of the evaporator to the condenser for various height differences in a gravity field. An understanding of the potential effects is necessary if these loop heat pipes are to be effectively employed.

#### **D. Thesis Contents**

Chapter One of this thesis contains an introduction to loop heat pipes and the specific problem to be evaluated. Chapter Two presents the approach taken to evaluate

the problem. Chapter Three describes the data and its analysis. Chapter Four presents a discussion of the results and finally Chapter Five presents conclusions and recommendations.

## II. Approach

### A. Introduction

This section will describe the experimental set up and present the various tests used to evaluate the loop heat pipe performance.

### B. Experimental Set-up

**1. Description of Pipe.** The loop heat pipe tested was known to have ammonia as the working fluid with a stainless steel enclosure (Beam, 1994). The wick structure material is unknown. The evaporator heat input section was 1.2 cm in diameter and was mounted in an 8.0 cm by 3.0 cm by 1.8 cm block. The evaporator reservoir section on the outside end was 1.2 cm in diameter by 9.4 cm long and on the inside end was 1.9 cm in diameter by 9.4 cm long (see Figure 2.1). The condenser heat removal section was 1.2 cm

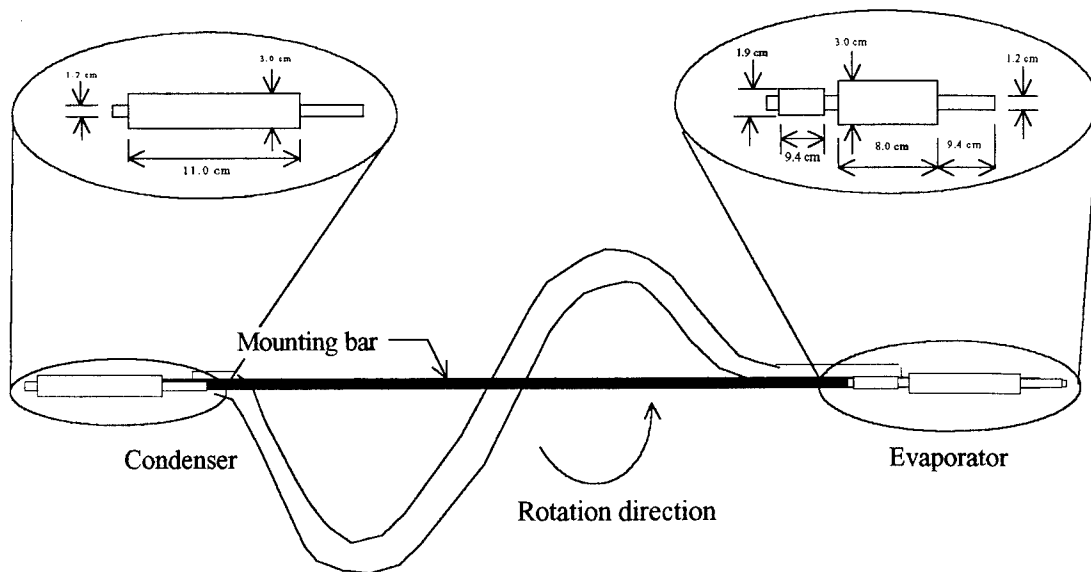


Figure 2.1 Loop Heat Pipe Test Set-up

in diameter and was mounted in an 11.0 cm by 3.0 cm by 1.8 cm block. The vapor and liquid lines were both 3.0 millimeters outside diameter and 3.48 meters long.

**2. Description of Pipe Layout.** The heat pipe was mounted on a 3.05 meter bar which was allowed to rotate about a rotation axis perpendicular to the page of Figure 2.1. Since the bar was shorter than the length of the heat pipe, the length of the vapor and liquid lines were arranged such that they formed a large 'S' shape (see Figure 2.1).

Throughout the testing, the arrangement of the lines varied to allow positioning at the desired evaporator and condenser angular orientations. The evaporator and the condenser were mounted on plates, which allowed their independent rotation of  $\pm 90$  degrees with respect to the axis of the mounting bar. These plates facilitated all desired relative angular orientations between evaporator and condenser for all mounting bar positions.

**3. Instrumentation of the Pipe.** The pipe was instrumented with copper constantan 30 SWG nylon insulated thermocouples throughout. Along the evaporator end of the pipe, two thermocouples were mounted to the end reservoir, three to the actual evaporator section, one to the adiabatic section, and two to the inside end reservoir (see Figure 2.2). The center thermocouple on the heat input section of the evaporator was used to provide input to the safety controller. At 13 locations along the liquid and vapor lines, adjacent pairs of thermocouples were mounted, one thermocouple on the vapor line and one on the liquid line. At the condenser end, five thermocouples were placed for temperature measurements.

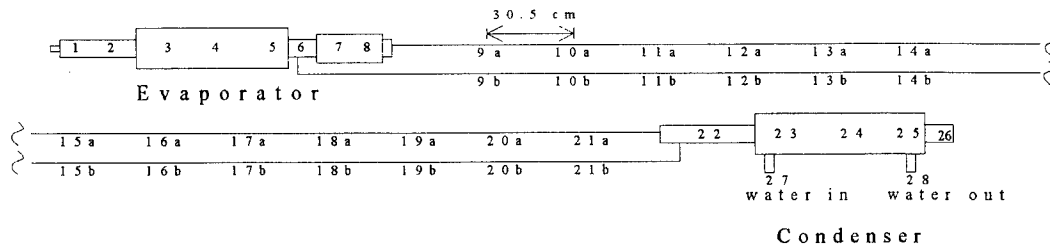


Figure 2.2 Thermocouple Locations

The pipe was insulated throughout with 1.27 cm thick black foam pad. An additional thermocouple was mounted on the exterior of the foam insulation at the evaporator. All thermocouples, except for the safety controller thermocouple, were input to a Fluke data logger for data acquisition.

**4. Test Equipment and Data Acquisition Equipment.** Heat input to the evaporator was supplied with electrical resistance heating. The amount of input power was determined from the value of the heaters resistance and the measured current flowing through it. To supply power to the heater, a Sorensen model number DCR 600-1.5B, 0-600 V, 0-3 Amp power supply was used. The layout of the equipment is shown in Figure 2.3. A summary of the equipment used is found in Table 2.1.

To measure the current and the power going to the heater, a Magtrol Power Analyzer, model 4612B power meter was used. The DC current to the evaporator heater was run through the power meter. This meter was used as a quality check to compare with the values measured by the Fluke data logger.

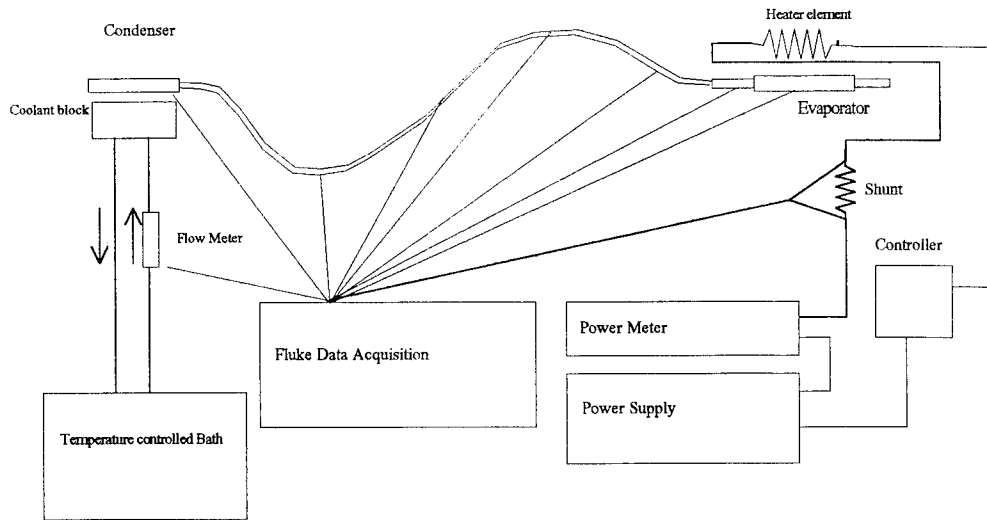


Figure 2.3 Test Equipment Layout

A precision resistor shunt was used as a means of measuring the current, which could then be recorded in the data logger. The current was used with the known heater resistance to determine the input power to the evaporator.

The Fluke data logger was the central component of the data acquisition system. The logger was programmed to scan all input channels every two minutes. The channels included all thermocouples and voltage measurements. The voltage measurements taken were those used to determine the current through the heater (the voltage across the shunt) and the voltage provided by the flowmeter circuitry, which indicated coolant flow rate at the condenser. Additional data items logged were: the ambient temperatures, and the coolant input and output temperatures. The data logger accomplished all necessary calculations, determining thermocouple temperatures and unit conversions required for finding input and output power. Additionally, the data logger was programmed to determine the steady state operating condition of the pipe (by checking if the average

condenser temperature had changed by less than 0.15 °C over a two minute interval).

Once a steady state was attained, the data logger saved all data points to disk upon each scan.

A controller was set up to ensure the pipe did not exceed a 60 °C maximum operating temperature, set to prevent rupture of the pipe. To prevent exceeding the temperature limit, the controller monitored the center thermocouple on the evaporator. When the controller detected the temperature was above the limit it shut off input power to the evaporator heater.

A flow meter, along with input and output thermocouples immersed in the coolant flow, determined the heat output at the condenser. The heat output at the condenser was used as a check to determine if the pipe was operating.

### **C. Tests Performed**

In all, 48 tests were performed. The first two tests were used to insure all testing and data acquisition equipment were functioning properly. The remaining tests and their configurations are given in what follows. A complete listing of the tests and the various orientations is included in Appendix D.

**1. Specific Configurations Tested.** To determine the loop heat pipe performance, tests were run at varying relative evaporator and condenser angles, and at varying relative heights of evaporator-over-condenser, and condenser-over-evaporator.

**i. Varying Relative Angles.** With the evaporator and condenser at the same relative height, the angle of the evaporator was varied keeping the condenser horizontal.



Table 2.1 Equipment Used

| Equipment                       | Manufacturer     | Model number                 | Accuracy   |
|---------------------------------|------------------|------------------------------|--|
| Data Acquisition                | Fluke            | 2286 Data Logging System     | Temperature: $\pm 0.65$ °C<br>Voltage:<br>range: 64mV; 0.01% + 8.0 $\mu$ V<br>range: 512mV; 0.01% + 40 $\mu$ V<br>range: 8V;<br>0.01% + 800 $\mu$ V<br>range: 64V; 0.02% + 4mV |
| Power Analyzer                  | Megtrol          | 4612B                        | 0.2% of reading or 0.25% of full scale   |
| Power Supply                    | Sorensen         | DCR 600-1.5B                 | Voltage: 0.1%<br>Current: 0.25%  |
| Controller                      | Honeywell        | DC 3003-0-00B-2-0 0-0111     | 0.20% full scale (temperature °C)  |
| Refrigerated and Heated coolant | Forma Scientific | 2095                         | at 20 °C $\pm 1$ °C  |
| Flow meter                      | Omega            | FTB 601                      | $\pm 1\%$ of reading   |
| Shunt                           |                  |                              | 1%   |
| Heater                          | Minco            | HK 14942 (-)<br>DC 9038/9405 | $\pm 1$ $\Omega$ at 23°C   |

Then the angle of the condenser was varied keeping the evaporator horizontal (see Figure 2.4). The angles evaluated included +135, +90, +45, 0, -45, and -90 degrees, for the evaporator and +90, +45, 0, -45, and -90 degrees for the condenser. The heat input block of the evaporator and the heat rejection block of the condenser were used for measuring the angles. These tests were included to determine the influence of relative angular orientation of the evaporator (and condenser) with respect to a gravity field. Ideally it was

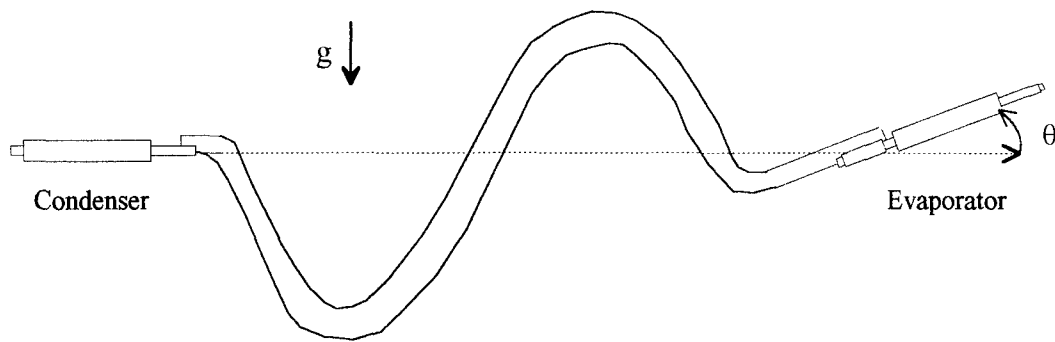


Figure 2.4. No Relative Height, Varying Angular Orientations

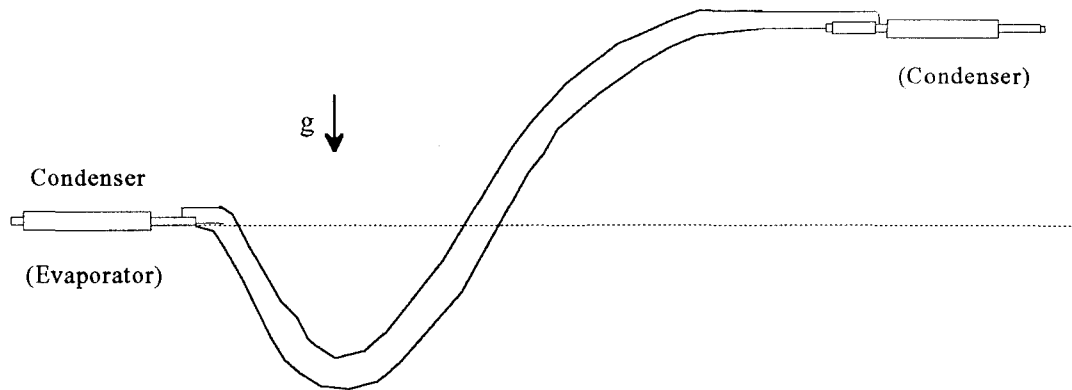


Figure 2.5. Varying Relative Height, Fixed Horizontal Angular Orientation

intended to provide insight into the magnitude of the effects of angular orientation only, since the evaporator and condenser were at the same relative height.

**ii. Varying Relative Heights.** In order to determine the performance of the loop heat pipe for relative height differences, the evaporator and condenser angles were fixed to zero degrees relative to horizontal, and the height of the evaporator over the condenser was varied, as well as the condenser height over the evaporator (see Figure

2.5). The height differences the loop heat pipe was evaluated at included: 0, 0.61, 1.22, 1.83, 2.44, and 2.79 meters.

**iii. Varying Relative Heights and Angles.** With the evaporator above the condenser, the angle of the evaporator was varied while fixing the condenser angle at a horizontal position (see Figure 2.6). The angles evaluated were again: +90, +45, 0, -45, and -90 degrees. The heights of the evaporator over the condenser that these test were run at included: 0, 1.22, and 2.44 meters. These tests were to provide insight into the influence of the evaporator heights and angular orientation on performance.

For the same evaporator-over-condenser heights, the evaporator was fixed at the horizontal position and the condenser angle allowed to vary (see Figure 2.6). The angles evaluated were again: +90, +45, 0, -45, and -90 degrees. This series of tests was to provide insight into the influence of the condenser orientation on performance.

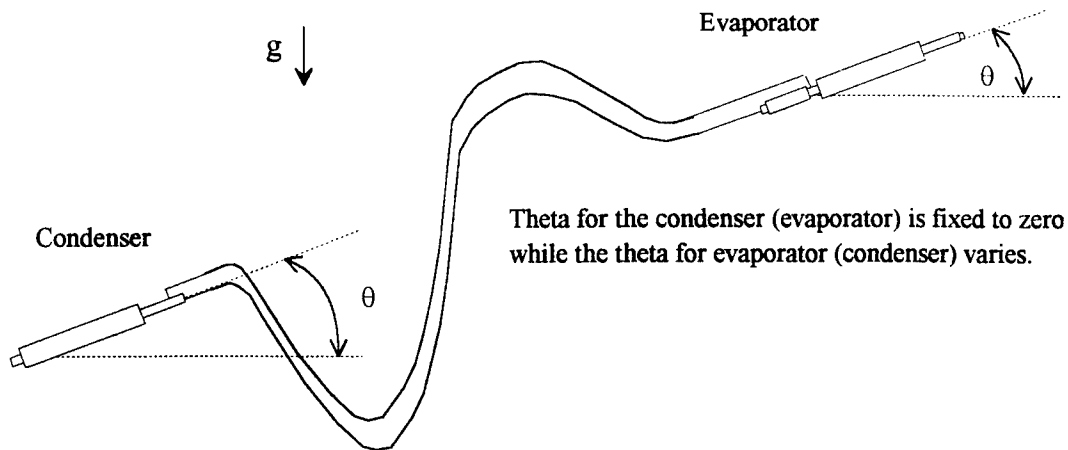


Figure 2.6

Varying Evaporator Heights and Evaporator and Condenser Angular Orientations

**2. Heat Input.** The envelope of heat inputs for the tests ranged from a typical low of 15 watts to a high of up to 125 watts. A low of 15 watts was attempted for all test. Some testing was accomplished in which heat inputs as low as 3 watts were attained. The upper heat input setting was determined by the evaporator temperature, where the evaporator temperature was kept below 60 °C to prevent pipe rupture.

**3. Coolant Temperatures.** For the initial tests, with no relative height difference between the evaporator and condenser (Figure 2.4), the tests were run with the coolant inlet temperature set at 20 °C and 40 °C. The remaining test configurations were run only at a 20 °C coolant temperature. These two temperatures were chosen to represent temperatures which may be experienced on an aircraft. The 20 °C coolant temperature was used for the majority of the tests since the coolant bath equipment easily maintained this temperature, whereas the 40 °C coolant temperature required additional manually controlled heaters. The coolant flow rate was set between 0.1 to 0.2 liters per minute. No attempt was made to control the condenser temperature.

### **III. Data Description and Analysis**

This section presents the criteria used for evaluating the loop heat pipe's performance, and defines the data reduction accomplished to develop the graphs used for evaluating the performance. The section ends with a discussion of the uncertainty analysis.

#### **A. Evaluation Criteria**

One measure of a heat pipes performance is the difference in temperature ( $\Delta T$ ), between the evaporator and the condenser, required to maintain the transfer of heat energy. The smaller the temperature difference for a given energy throughput, the better the heat pipe performance. This temperature difference was used as the primary indicator of heat pipe performance.

The  $\Delta T$  is plotted against the heat input at the evaporator ( $Q_{in}$ ). The heat input to the evaporator is used since its value is known more accurately than the heat output. As such, analysing the  $\Delta T$  as a function of  $Q_{in}$  will provide an indication of the loop heat pipe's ability to transfer heat energy away from a source.

#### **B. Data Description and Reduction**

Data was recorded from all thermocouples mounted on the pipe. However, for the analysis, only the heat input to the evaporator and the temperature of the evaporator and condenser were used.  $Q_{in}$  was determined by measuring the voltage across a shunt resistor

in series with the evaporator heater. Knowing the shunt resistance, voltage across it, and the resistance of the heater, the power,  $Q_{in}$ , was calculated. It is assumed that the majority of the heat input is delivered to the evaporator. Appendix C calculates the estimate of the  $Q_{in}$  to the evaporator which is convected away. The maximum amount found to be convected away at the evaporator was less than 1.2 watts. The pipe was equipped to monitor heat out flow at the condenser. A heat balance was accomplished on the pipe by measuring the heat taken out at the condenser. This was done by measuring the flow rate of the coolant to the coolant block and measuring the inlet and exit temperatures of the coolant. The heat removed from the coolant block was calculated using the specific heat of the coolant, the coolant flow rate, and the difference between coolant inlet and exit temperatures. For the majority of the tests the heat removed was within the experimental uncertainty of the measurements. For the tests where the heat removed was not within the experimental uncertainty the loss was attributed to parasitic losses through the insulation.

The definition of a data point used for analysis is the steady state  $\Delta T$  vs  $Q_{in}$ . To determine the  $\Delta T$  for each data point, the two thermocouple temperatures on the evaporator were averaged as well as the three thermocouple temperatures on the condenser and the difference between them used as the  $\Delta T$ . To determine when the pipe was at steady state the average condenser temperature was used. Steady state was defined to be less than a 0.15 °C temperature change over a two minute interval while maintaining the heat input at a constant value. These data were taken for a total of 46 tests for various relative angular and height orientations.

To reduce the data for plotting, the data was reviewed and all non steady state data points removed. Then, at each heat input setting, the steady state points were averaged. With the exception of the first ten tests, data was taken to insure at least five steady state points at each heat input setting were recorded for averaging. After the tenth test it was decided that to ensure a steady state condition, additional settling time would be provided. A sample of the data recorded is included as Appendix B. The data was reduced to produce graphs of  $\Delta T$  vs  $Q_{in}$ . These graphs were then combined with one another to compare the effects of angular orientation of evaporator and condenser and to assess the effect of angular orientation in combination with height differences.

### **C. Uncertainty Analysis**

The uncertainty in the  $\Delta T$  is fixed for all data taken and was determined to be  $\pm 1.30$  °C. The uncertainty for  $Q_{in}$  is approximately 5.0% of the input setting (see Appendix C for uncertainty calculations).

## **IV. Discussion of Results**

This chapter will focus on the results of the testing accomplished. It begins by comparing the influences of coolant inlet temperature, angular orientations, and the height differential between components on the performance of the LHP. The chapter goes on to relate other items of interest observed during the testing, and finally concludes with a presentation of the factors which contribute to performance degradation.

### **A. Discussion of Graphs**

Much of the comparative analysis between tests is related in terms of the negative or positive slope of the  $\Delta T$  vs.  $Q_{in}$  graphs. As mentioned in Chapter Three, the  $\Delta T$  is a measure of the LHP's performance. Therefore, knowledge of how the  $\Delta T$  is influenced by coolant inlet temperatures, angular orientations, and height differences is of interest.

The balance of this thesis will compare the  $\Delta T$  vs  $Q_{in}$  graphs at the various orientations. The figures are arranged to first present the varying evaporator and condenser angle effects at the various heights, which account for eight sets of graphs. The remaining two sets of graphs present the effects of varying heights at fixed horizontal angles.

**1. Comparison of Varying Evaporator Angles for 20 °C and 40 °C Coolant Inlet Temperatures at No Relative Height Difference.** In this section the effects on performance of coolant inlet temperature and evaporator angles will be discussed.

#### **i. Varying Evaporator Angles at 40 °C Coolant Inlet Temperature.**

Figure 4.1 contains the varying evaporator angle graphs for the 40 °C coolant inlet



temperature where there is no relative height difference between evaporator and condenser. The graphs in Figure 4.1 indicate that the LHP operates only in a positive slope range for all angular orientations and heat inputs. This trend of increasing  $\Delta T$  with increasing heat input is what would be expected for a conventional heat pipe. The tight grouping of the graphs appear to indicate there is no evaporator angular dependence on

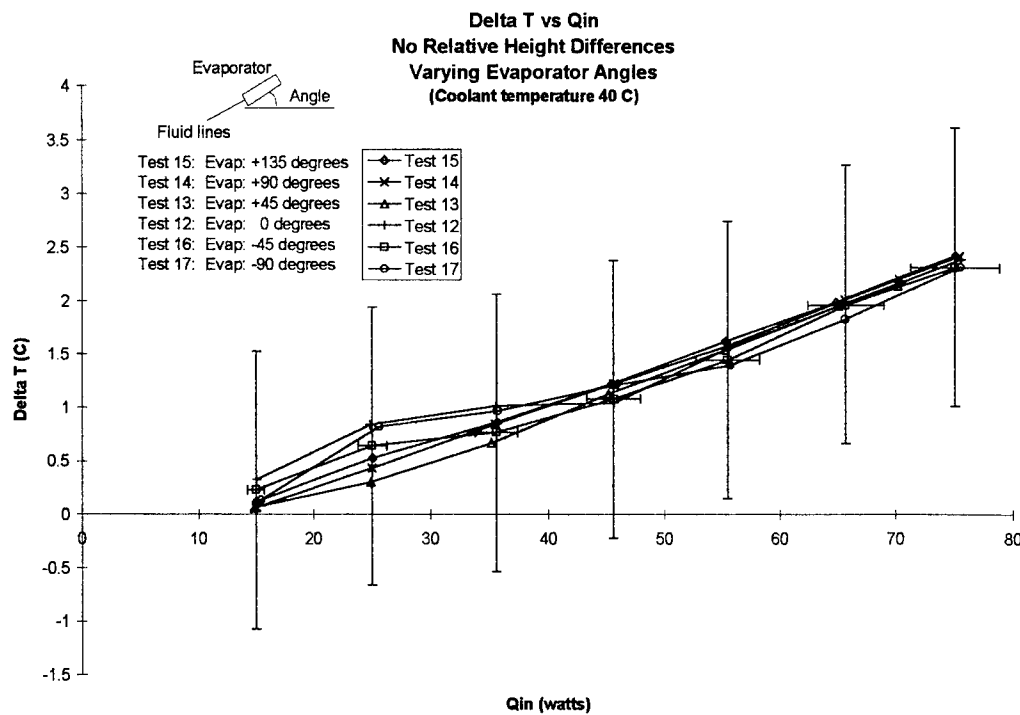


Figure 4.1 Delta T vs  $Q_{in}$ , No Relative Height Differences, Varying Evaporator Angles, 40 °C Coolant Temperature

performance at the 40 °C coolant inlet temperature. It was also noted that for all evaporator angular orientations at a coolant inlet temperature of 40 °C, the LHP operated successfully down to a  $Q_{in}$  of 15 watts. Successful operation was defined to be a steady evaporator and condenser temperature at a given steady heat input.

## ii. Varying Evaporator Angles at 20 °C Coolant Inlet Temperature.

Figure 4.2 contains the varying evaporator angle graphs for the 20 °C coolant inlet temperature where there is no relative height difference between evaporator and condenser. From Figure 4.2, the graphs are fairly tightly grouped for  $Q_{in}$  greater than 40 watts. However, below 40 watts the  $\Delta T$  increases with decreasing  $Q_{in}$ , or equivalently, there is a negative slope at the lower  $Q_{in}$  values. This negative slope is not found for all angular orientations, but only at those orientations which successfully operated at 15 watts. Only the +135, 0, and -45 degree evaporator angles operated successfully at 15 watts. For the positive slope regions with  $Q_{in}$  greater than 40 watts, the  $\Delta T$  at a given  $Q_{in}$

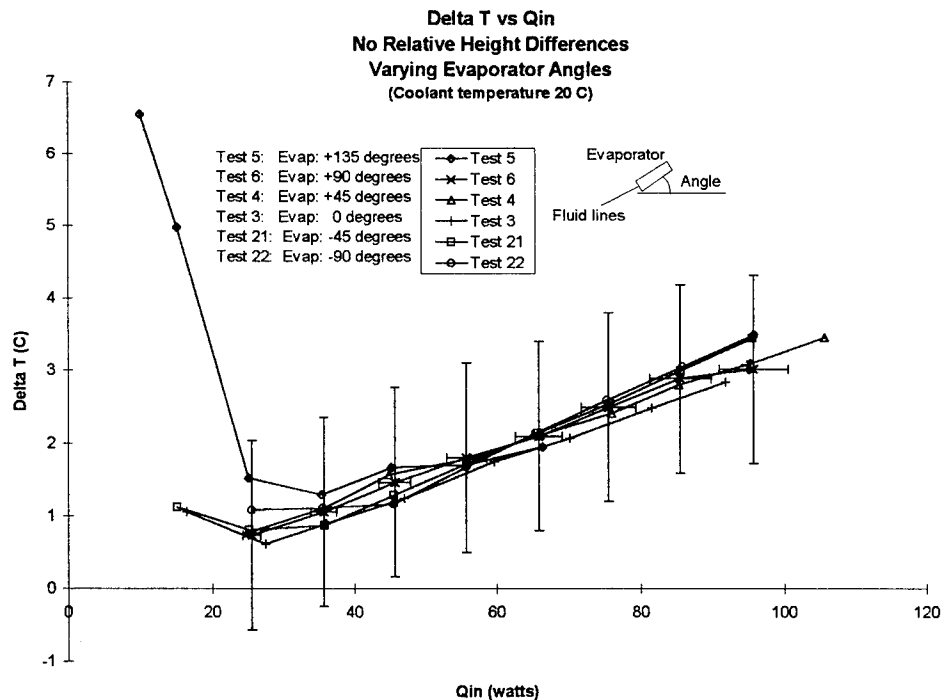


Figure 4.2 Delta T vs  $Q_{in}$ , No Relative Height Differences, Varying Evaporator Angles, 20 °C Coolant Temperature

did not vary significantly between the various evaporator angular orientations. The  $\Delta T$  variation was less than 0.5 °C.

**2. Comparison Of Varying Condenser Angles for 20 °C and 40 °C Coolant Inlet Temperatures at No Relative Height Difference.** In this section the effects on performance of coolant inlet temperature and condenser angles will be discussed.

**i. Varying Condenser Angles at 20 °C Coolant Inlet Temperature.** Figure 4.3 contains the varying condenser angle graphs for the 20 °C coolant inlet temperature where there is no relative height difference between evaporator and condenser. In Figure 4.3 one observes a distinct stratification of the graphs, which points to a condenser angular orientation dependence on performance. Here, just as for the varying evaporator angular orientations with a 20 °C coolant inlet temperature (Figure 4.2), below a heat input of 40 watts the slope is generally negative. However, comparing the varying evaporator angular orientations to the varying condenser angular orientations for a 20 °C coolant inlet temperature at a  $Q_{in}$  of 15 watts, Figure 4.2 versus Figure 4.3, the LHP successfully operated at all condenser angles, where it did not for all evaporator angles. This may indicate that operation at low  $Q_{in}$  is more sensitive to evaporator angular orientations than condenser angular orientations. This is most likely due to the LHPs particular internal construction in combination with the low mass flow rate.

There are two potential explanations for the negative followed by positive slopes of the graphs. The first is given by Dickey and Peterson (1994). They account for the phenomenon using the pressure temperature properties of the working fluid and the Clausius-Clapeyron relationship.

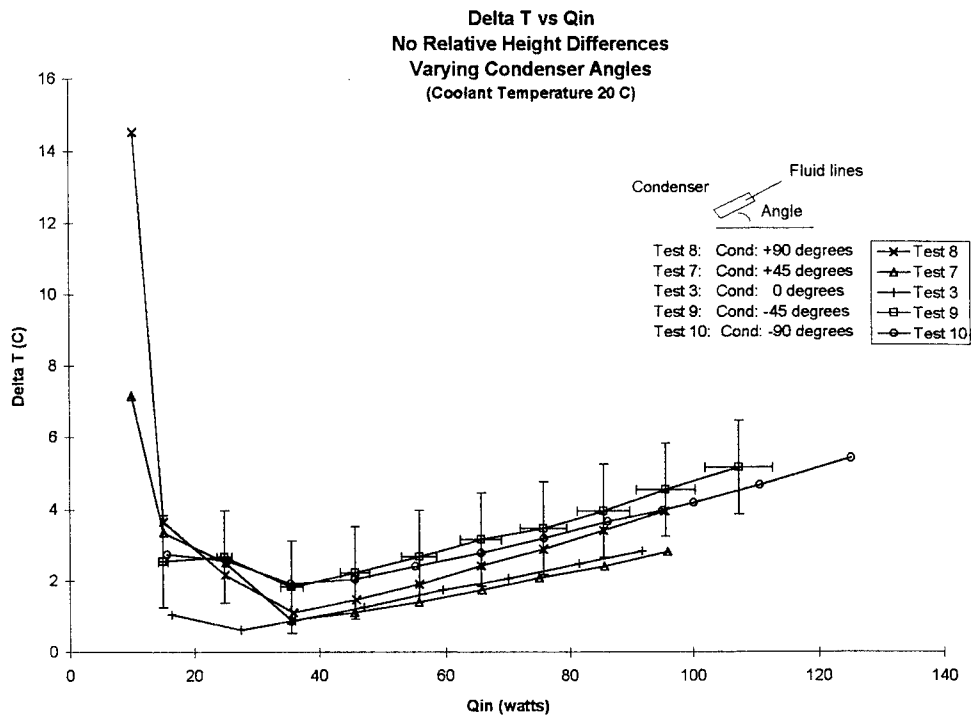


Figure 4.3 Delta T vs  $Q_{in}$ , No Relative Height Differences, Varying Condenser Angles, 20 °C Coolant Temperature

The Clausius-Claperon relationship is given as,

$$\Delta P_t = \frac{h_{fg} P_v \Delta T_w}{RT_v^2} \quad \text{Eqn 4.1}$$

where  $\Delta T_w$  is the temperature difference across the wick,  $\Delta P_t$  is the pressure difference developed across the wick due to the temperature difference across the wick,  $P_v$  is the vapor pressure,  $T_v$  is the vapor temperature and R the gas constant for the vapor. For low input power the system pressure must be high enough to account for the small  $\Delta T_w$ , which is due to the low mass flow rate through the wick. With the low mass flow rate, insufficient sub-cooled liquid reaches the evaporator to maintain much of a temperature difference across the wick. From the Clausius-Claperon relationship, to make up for pressure losses in the LHP, a higher vapor pressure is required. Due to the pressure

temperature properties of the working fluid, the higher vapor pressure can only be attained with a higher temperature, thus a higher evaporator temperature. As the input power is increased there is a larger mass flow rate, with the increased mass flow rate there is an increase in the temperature difference across the wick (due to the sub-cooled liquid on the liquid side of the wick) with a corresponding decrease in the required vapor pressure and a subsequent decrease in vapor temperature.

The second theory explaining the negative slope formation is that the condenser is full of liquid and must be cleared of the liquid to make available surface area for the vapor to condense on. With less vapor condensed, the vapor pressure continues to increase until the pressure is sufficient to push the liquid up and out of the condenser. Again, from the pressure temperature properties of the working fluid, the higher pressure can only be attained with a higher temperature, thus, a higher evaporator temperature.

#### **ii. Varying Condenser Angles at 40 °C Coolant Inlet Temperature.**

Figure 4.4 contains the varying condenser angle graphs for the 40 °C coolant inlet temperature where there is no height difference between evaporator and condenser. From Figure 4.4, there is again the stratification of the varying condenser angle graphs as found in Figure 4.3. However, for the 40 °C coolant inlet temperature no real negative slope region of the graphs is evident for either varying evaporator or varying condenser angles (Figure 4.1 and Figure 4.4). This shows a clear dependence of performance on the operating temperature, with the improved performance being for the higher coolant inlet temperatures (improved performance being a smaller  $\Delta T$ ). However, there is a trade off.

At the higher coolant inlet temperatures the LHP cannot transport as much heat due to the maximum operating temperature limit placed on the evaporator.

**3. Comparison of Varying Evaporator Angles at Evaporator-Over-Condenser Height Differences of: 0 meters, 1.22 meters, and 2.44 meters.** In this section the existence of a negative slope region on the  $\Delta T$  vs  $Q_{in}$  graphs will be discussed along with the shifting of the transition point at which the slope changes from negative to positive. Additionally, the minimum  $Q_{in}$  observed for evaporator angles is discussed, and finally the optimum evaporator angle for the minimum  $\Delta T$  is noted.

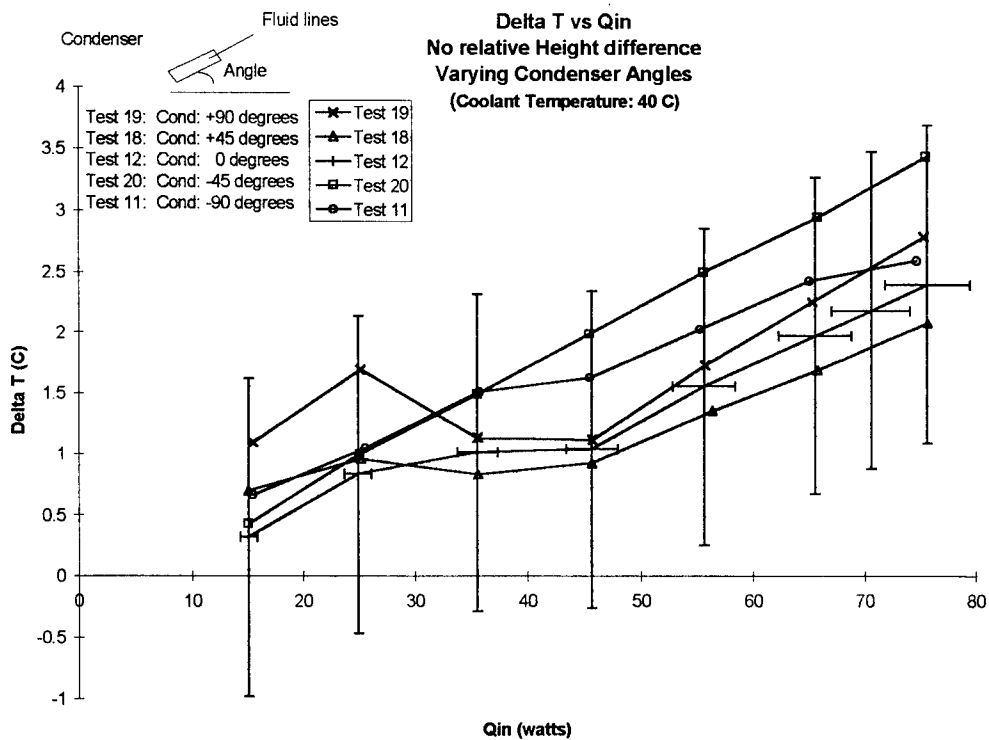


Figure 4.4 Delta T vs  $Q_{in}$ , No Relative Height Differences, Varying Condenser Angles, 40 °C Coolant Temperature

### **i. Varying Evaporator Angles at Evaporator-Over-Condenser Height**

**Difference of 1.22 meters.** Figure 4.5 contains varying evaporator angle graphs for an evaporator-over-condenser height difference ( $\Delta H$ ) of 1.22 meters where the coolant inlet temperature is 20 °C. In Figure 4.5, the  $Q_{in}$  point at which the slope transitions from negative to positive, appears to depend on evaporator angular orientation. This is evidenced by the initiation of the negative slope for the 0 degree evaporator angle taking place at a  $Q_{in}$  of 45 watts versus the initiation of the negative slopes for the other evaporator angles taking place near 20 watts  $Q_{in}$ . Additionally, whether or not there is a transition from a negative to a positive slope appears to be dependent upon evaporator angle. This is shown by the fact that for evaporator angles of +90 and +45 degrees there is no negative slope region. For those evaporator angles with no negative slope, there is an associated increase in the minimum  $Q_{in}$  required to maintain LHP operation. For the +90 degree evaporator angle, the LHP would not continue to operate below a  $Q_{in}$  of 20 watts and for the +45 orientation the LHP was not operated below a  $Q_{in}$  of 45 watts. For the orientations where the LHP has a negative slope, that is at heat inputs of less than 20 watts, the best performance (lowest  $\Delta T$ ) was for the -90 degree evaporator orientation, followed by the -45, and 0 degree orientation. Throughout the positive slope region, above the transition points from negative to positive slope, there is no indication of a performance dependence on evaporator angular orientation.

### **ii. Varying Evaporator Angles at Evaporator-Over-Condenser Height**

**Difference of 2.44 meters.** Figure 4.6 contains varying evaporator angle graphs for an evaporator-over-condenser height difference of 2.44 meters where the coolant inlet

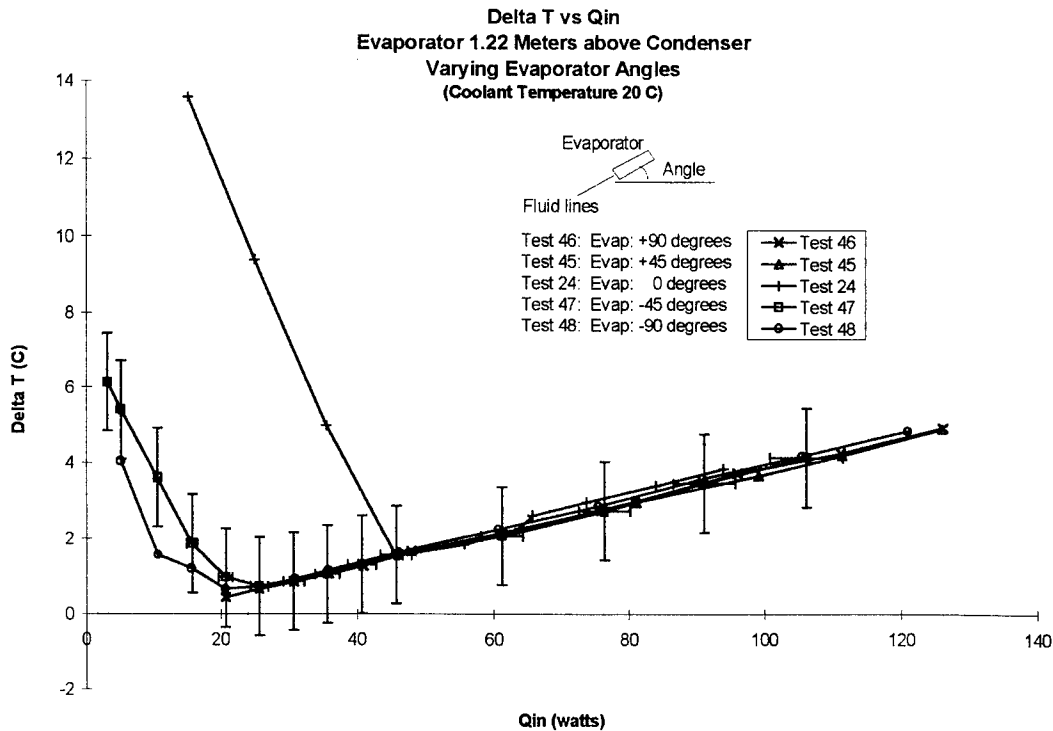


Figure 4.5 Delta T vs  $Q_{in}$ , 1.22 meter Height Difference, Varying Evaporator Angles, 20 °C Coolant Temperature

temperature is 20 °C. From Figure 4.6, there are also evaporator angles at which no negative slope is observed. These angles are the same as for the  $\Delta H$  of 1.22 meters, +95, and +45 degrees (Figure 4.5). For the varying evaporator angles at which there is a negative slope, the transition points are within 10 watts of each other. This indicates that the  $Q_{in}$  point at which the slopes change is only slightly dependent upon evaporator angular orientation. In comparison, for a  $\Delta H$  of 1.22 meters (Figure 4.5), the point at which the slopes shift from negative to positive is much more varied, ranging from 20 watts for two of the evaporator angles to 45 watts for the horizontal evaporator angle.

In general there appeared to be a minimum  $Q_{in}$  for each of the evaporator angles where a negative slope failed to develop. Trying to determine what the minimum  $Q_{in}$  was



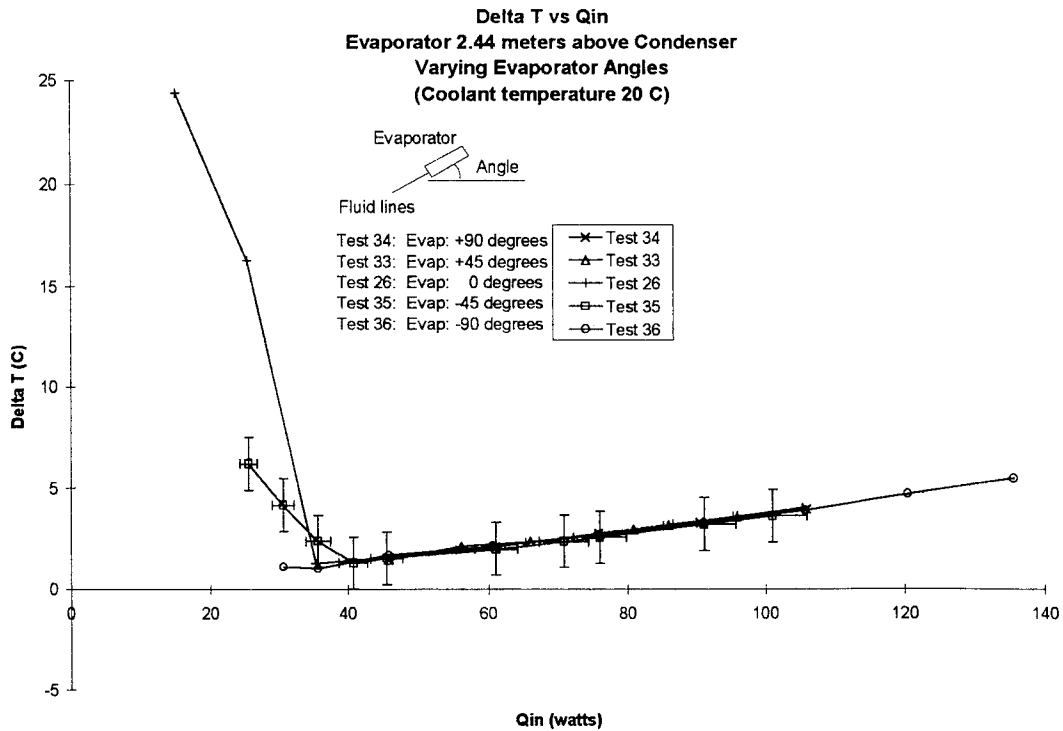


Figure 4.6  $\Delta T$  vs  $Q_{in}$ , 2.44 meter Height Difference, Varying Evaporator Angles, 20 °C Coolant Temperature

for different  $\Delta H$  was complicated by the fact that the  $Q_{in}$  minimum was found to be sensitive to the rate at which the  $Q_{in}$  was reduced. This rate sensitivity was not observed until later on in the testing (this observation is more fully discussed in section 4 B). Thus, a comparison of minimum  $Q_{in}$  for the no negative slope evaporator angles between different heights would be of questionable accuracy, but may provide insight to general trends.

Comparing between a  $\Delta H$  of 1.22 meters and 2.44 meters, for the angles with no negative slope, it was found a greater  $Q_{in}$  minimum is required at the greater  $\Delta H$ , 45 watts versus 20 watts. These  $Q_{in}$  minimum are the minimums that were tested at. As mentioned

above, it may be possible to operate the pipe for these orientations at a lower  $Q_{in}$ . A summary of the evaporator angles tested and the observance of a negative or positive slope, along with the minimum  $Q_{in}$  tested is presented in Table 4.1.

For the orientations where the LHP had a negative slope region at the 2.44 meter  $\Delta H$ , the best performance (lowest  $\Delta T$ ) was for the -45 degree orientation, followed by the horizontal orientation. The most significant result that these graphs reveal is that for the positive slope region, the performance appears to be independent of evaporator angular orientation, while the formation of a negative slope region does appear to be sensitive to evaporator angular orientations.

A potential explanation for the lack of heat pipe operation at the lower  $Q_{in}$  values, for the positive evaporator angles, may be attributed to the placement of the vapor line entrance within the evaporator. The interior design at this point is unknown so one can only speculate. However, what may be occurring is liquid flooding thru the wick, obstructing the entrance to the vapor line. Figure 4.7 shows potential orientations where the vapor line would be obstructed. If liquid is obstructing the vapor line this would require a high vapor pressure, with the associated increased temperature, to push the liquid out of the way or push the liquid down the vapor line. To attain the higher temperatures requires a higher heat input, thus operation is not observed when the  $Q_{in}$  is too low to attain the required temperatures.

**4. Comparison of Varying Condenser Angles at Evaporator-Over-Condenser Height Differences of: 0 meters, 1.22 meters, and 2.44 meters.** This section discusses the minimum  $Q_{in}$  operation point found for all condenser angular orientations and height

## Evaporator

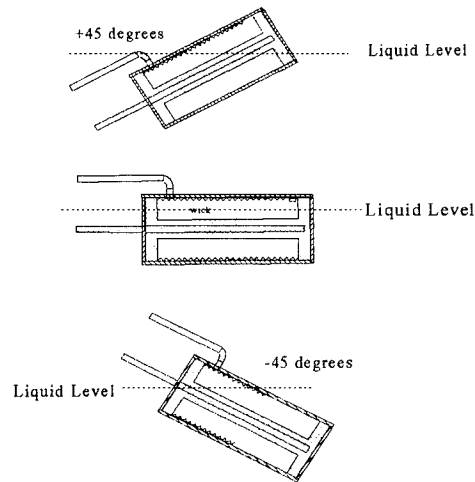


Figure 4.7 Obstruction of Vapor Line

differences, and discusses the existence of negative slope regions and the locations of the transition points where the slopes change from negative to positive.

**i. Varying Condenser Angles at Evaporator-Over-Condenser Height Difference of 1.22 meters.** Figure 4.8 contains varying condenser angle graphs for an evaporator-over-condenser height difference of 1.22 meters where the coolant inlet temperature is 20 °C. It is observed from Figure 4.8 that the LHP easily reached and maintained steady state operation at a  $Q_{in}$  of 15 watts. Additionally, all condenser angular orientations show the negative slope followed by a positive slope for increasing  $Q_{in}$ . For all condenser angles, the point at which the slopes change from negative to positive takes place near 45 watts  $Q_{in}$ . This is in contrast to the varying evaporator angles at a  $\Delta H$  of 1.22 meters (Figure 4.5), where the transition point was found to depend upon evaporator angle.

It is interesting to note that the transition point from negative to positive for the

Table 4.1 Varying Evaporator Angles and Heights, Summary Data

| Evaporator Angle (degrees) | $\Delta H$ (evaporator over condenser) (meters) | Coolant Inlet Temperature ( $^{\circ}\text{C}$ ) | Minimum $Q_{in}$ operated at (watt) | $Q_{in}$ at transition (negative to positive slope) |
|----------------------------|---|--|-------------------------------------|---|
| 135                        | 0   | 40   | 15                                  | no negative slope                                   |
| 135                        | 0   | 20   | 10                                  | 35  |
| 90                         | 0   | 40   | 15                                  | no negative slope                                   |
| 90                         | 0   | 20   | 25                                  | no negative slope                                   |
| 90                         | 1.22  | 20   | 20                                  | no negative slope                                   |
| 90                         | 2.44  | 20   | 45                                  | no negative slope                                   |
| 45                         | 0   | 40   | 15                                  | no negative slope                                   |
| 45                         | 0   | 20   | 25                                  | no negative slope                                   |
| 45                         | 2.44  | 20   | 45                                  | no negative slope                                   |
| 45                         | 1.22  | 20   | 45                                  | no negative slope                                   |
| 0                          | 0   | 40   | 15                                  | no negative slope                                   |
| 0                          | 0   | 20   | 15                                  | 25  |
| 0                          | 1.22  | 20   | 15                                  | 45  |
| 0                          | 2.44  | 20   | 15                                  | 35  |
| -45                        | 0   | 40   | 15                                  | no negative slope                                   |
| -45                        | 0   | 20   | 15                                  | 25  |
| -45                        | 1.22  | 20   | 3                                   | 25  |
| -45                        | 2.44  | 20   | 25                                  | 40  |
| -90                        | 0   | 40   | 15                                  | no negative slope                                   |
| -90                        | 0   | 20   | 25                                  | no negative slope                                   |
| -90                        | 1.22  | 20   | 5                                   | 20  |
| -90                        | 2.44  | 20   | 30                                  | 35  |

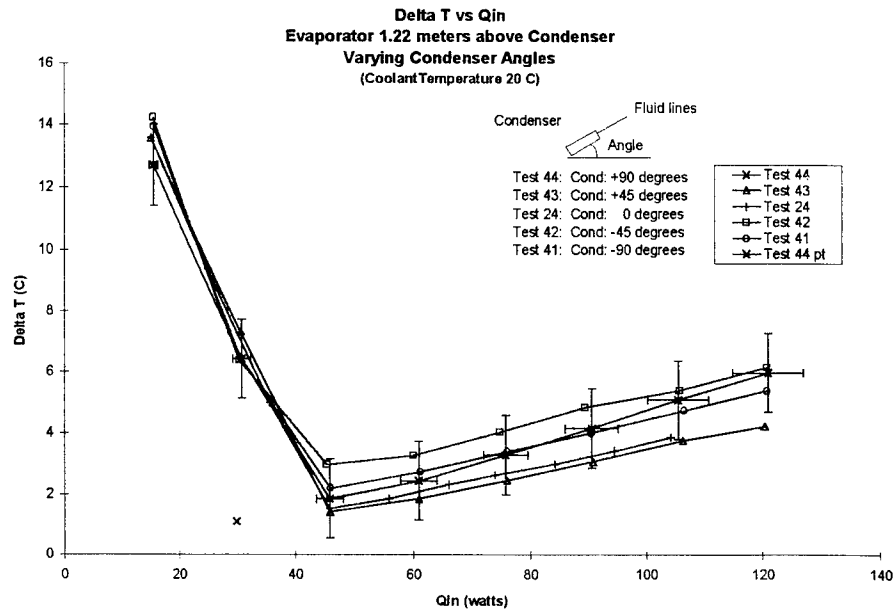


Figure 4.8 Delta T vs  $Q_{in}$ , 1.22 meter Height Difference, Varying Condenser Angles, 20 °C Coolant Temperature

condenser at 0 degrees (where both condenser and evaporator are horizontal, test 24) lines up with all the other condenser angle graphs of Figure 4.8. However, when comparing this transition point to the varying evaporator angular orientations at  $\Delta H$  of 1.22 meters (Figure 4.5), it is at a much higher  $Q_{in}$  than for the other evaporator angles (which have a negative to positive slope transition point). This suggests again the influence of evaporator orientation on performance.

**ii. Varying Condenser Angles at Evaporator-Over-Condenser Height Difference of 2.44 meters.** Figure 4.9 contains varying condenser angle graphs for an evaporator-over-condenser height difference of 2.44 meters where the coolant inlet temperature is 20 °C. It was observed in Figure 4.9, as well as for the  $\Delta H$  of 1.22 meters,

Figure 4.8, that the LHP reached and maintained steady state operation at a  $Q_{in}$  of 15 watts for all condenser angular orientations.

Comparing the varying condenser angle graphs of Figures 4.8 and 4.9, with the exception of the tests for the +45 and 0 degree angles, the two figures show the same general trends. However, the graphs at a  $\Delta H$  of 2.44 meters show a higher  $\Delta T$  at the 15 watt  $Q_{in}$  than those at a  $\Delta H$  of 1.22 meters. For the  $\Delta H$  of 2.44 meters, the  $\Delta T$  ranges from 18.69 °C to 24.94 °C, and at a  $\Delta H$  of 1.22 meters the  $\Delta T$  ranges from 12.71 °C to 15.42 °C. In contrast, when comparing the  $\Delta T$  at a  $Q_{in}$  of 75 watts, there is not as much difference between the two heights; at the  $\Delta H$  of 2.44 meters the  $\Delta T$  ranges from 2.34 °C to 3.75 °C, and at a  $\Delta H$  of 1.22 meters the  $\Delta T$  ranges from 2.62 °C to 4.02 °C. These

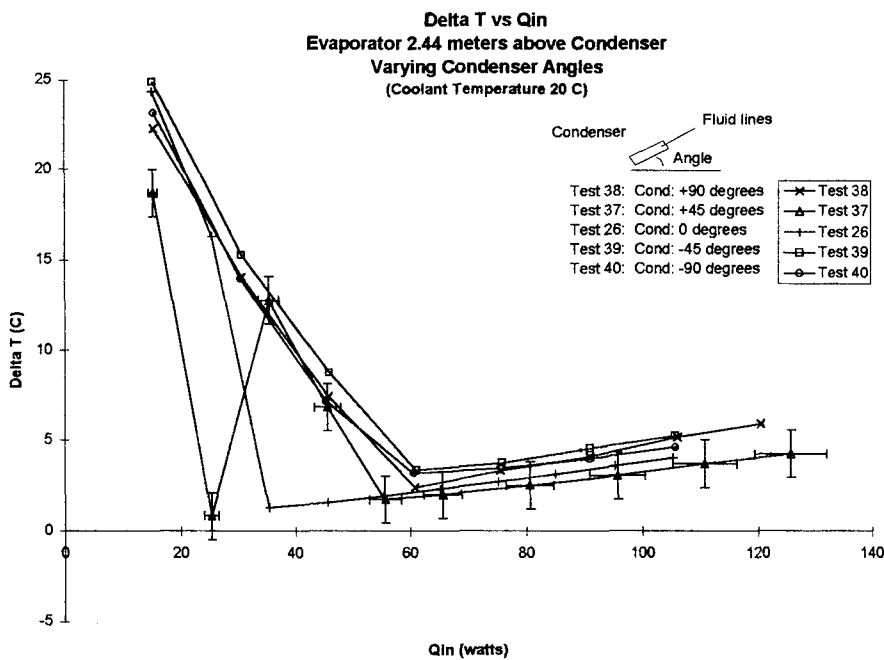


Figure 4.9 Delta T vs  $Q_{in}$ , 2.44 meter Height Difference, Varying Condenser Angles, 20 °C Coolant Temperature

results suggest that the height difference has its greatest influence at the low  $Q_{in}$  values, or equivalently, in the negative slope region of the graphs.

Of particular interest are the tests for the +45 and 0 degree condenser angles in Figure 4.9. These tests show a departure from what otherwise appears to be the normal trends for the LHP, especially when compared to the graphs of Figure 4.8, where all five graphs follow the same general trend. The departure of the results at 0 and +45 degrees from the other angular orientations indicates either an error in the data or some other phenomenon. Since the experimental procedures were not changed between tests, it is reasonable to eliminate the cause as an error, thus these differences must indicate some other phenomenon. This phenomenon is discussed further in section IV. B as a  $\Delta T$  anomaly.

**iii. Performance Dependence on Condenser Angular Orientation.** The performance of the LHP appears to be dependent upon the condenser angular orientation. At certain  $Q_{in}$  values, for all  $\Delta H$  and coolant temperatures the order of the lowest to highest  $\Delta T$  remains the same, that is to say, the same condenser angle has the highest  $\Delta T$ , or lowest  $\Delta T$ .

It is also noted that for all condenser graphs when  $Q_{in}$  is above 35 watts, there is a general trend of the +90 angle graphs to cross the -90 graphs. This trend showing the difference in slopes for these two condenser angles further indicates the dependence of performance on the orientation of the condenser. Specifically, it shows that the best orientation for performance, where the condenser is straight up or straight down, changes

with input power. For all condenser angles tested above 35 watts, the best condenser angle for performance (lowest  $\Delta T$ ) is +45 degrees and the poorest is -45 degrees.

Due to the uncertainty in the measurements it could be argued that performance based on condenser angular orientation is insignificant. However, the consistency of the  $\Delta T$  ordering of the graphs throughout all the relative height and temperature differences, plainly points out such a dependence.

### **5. Comparison of Varying Relative Heights at Fixed Horizontal Angular**

**Orientations.** The following section discusses the effects of height on LHP performance.

**i. Evaporator-Over-Condenser Orientations.** Figure 4.10 contains the graphs for varying evaporator-over-condenser height differences where the evaporator and condenser are fixed to the horizontal orientation and the coolant inlet temperature is 20 °C. It is observed in Figure 4.10 that there is a shift in the transition point at which the slope changes from negative to positive. The transition point appears to be related to the  $\Delta H$ . In general, the transition point shifts right with increasing  $\Delta H$ , the exception being the plot for the  $\Delta H$  of 2.44 meters. At this  $\Delta H$ , the transition point is near 35 watts. However, if this plot is compared to the majority of the graphs for the varying condenser angular orientations at this same  $\Delta H$  (Figure 4.9) the transition point would be found near 60 watts. This would appropriately place the transition point for the 2.44 meter plot in between the graphs for 1.83 and 2.79 meters, as seen in Figure 4.10 (where the transition point would be shifting right with increasing  $\Delta H$  or equivalently at a higher  $Q_{in}$ ). The



misplacement of the 2.44 meter  $\Delta H$  graph is most likely attributed to the previously mentioned  $\Delta T$  anomaly.

An additional result found for the various heights, is that once the pipe is operating in the positive slope region, the performance is only slightly related to  $\Delta H$ . However, there is an order from best to poorest performance, with the best (lowest  $\Delta T$ ) found for no height difference, and the poorest found at the 2.93 meter height difference. In the negative slope region, the best performance is found at the smaller  $\Delta H$ .

**ii. Condenser-Over-Evaporator Orientations.** Figure 4.11 contains the graphs for varying condenser-over-evaporator height differences where the evaporator and

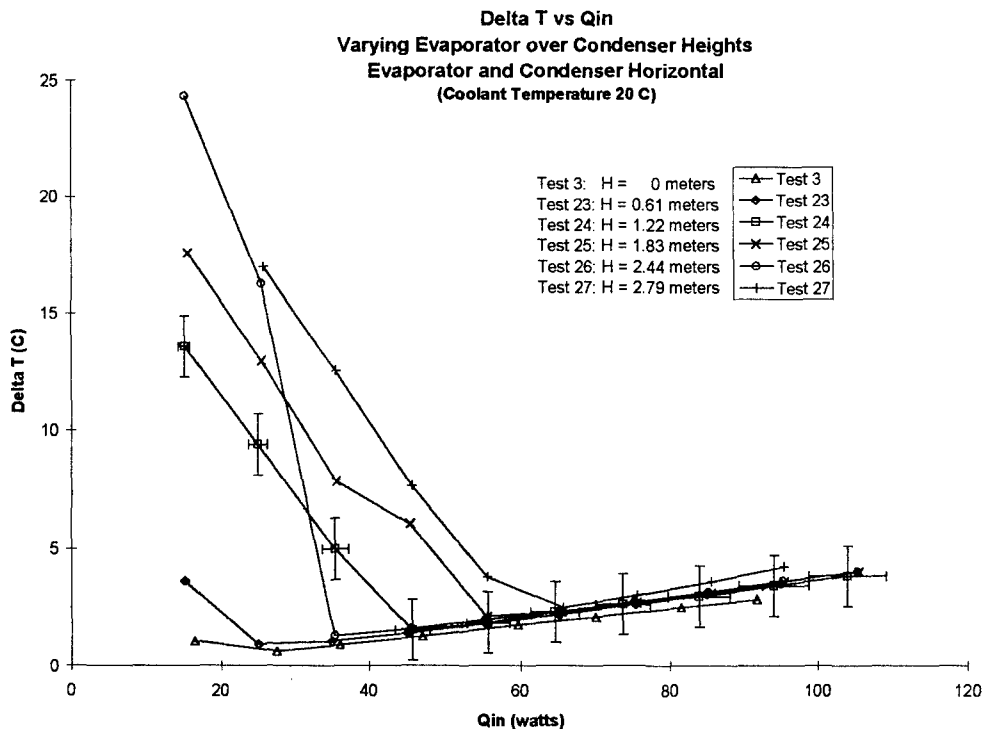


Figure 4.10 Delta T vs Q<sub>in</sub>, Varying Evaporator over Condenser Heights, Evaporator and Condenser Horizontal, Coolant Temperature 20 °C

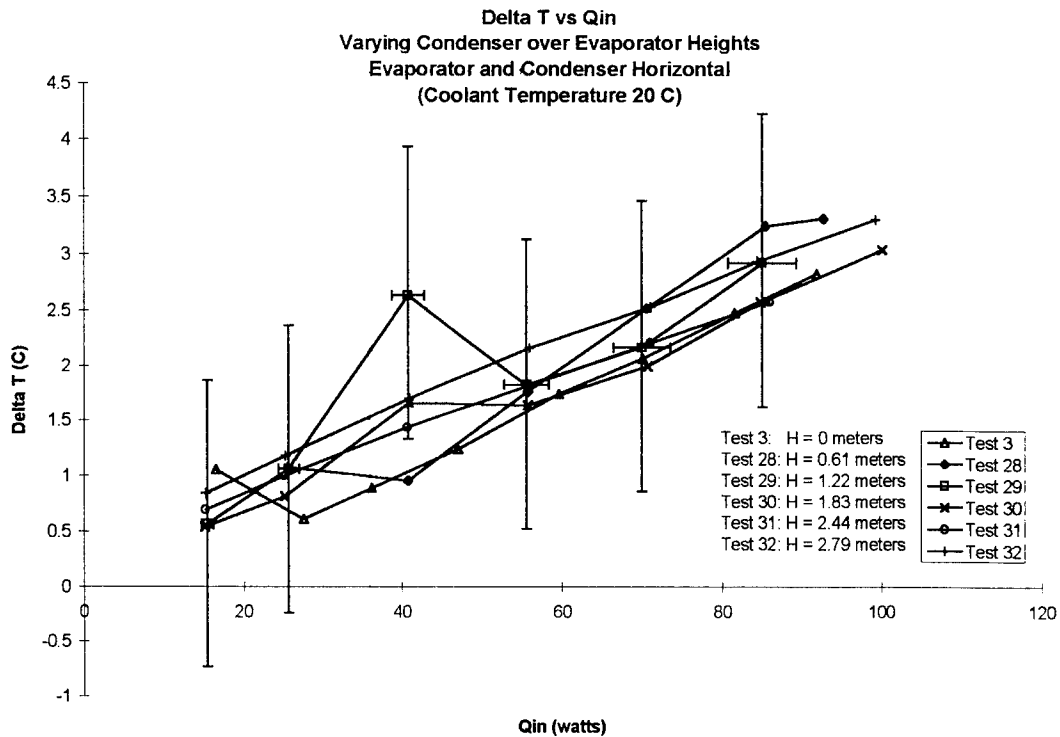


Figure 4.11 Delta T vs  $Q_{in}$ , Varying Condenser over Evaporator Heights, Evaporator and Condenser Horizontal, Coolant Temperature 20 °C

condenser are fixed to the horizontal orientation and the coolant inlet temperature is 20 °C. It is observed in Figure 4.11 that the  $\Delta T$  stayed below 4.0 °C for all heights and  $Q_{in}$  tested. Additionally, the LHP continued to operated successfully at 15 watts for all  $\Delta H$  with the condenser over the evaporator. The data for these tests seems somewhat more sporadic than for other tests. However, the LHP does appear to operate, within the uncertainty bounds, in a positive slope range for all power and height orientations. A potential explanation for the sporadic graphs may be due to the particular orientation of the liquid and vapor lines.

**6. Trends Attributable to Coolant Inlet Temperature.** This section discusses the effects on performance of coolant inlet temperature. The effects referenced are for the no relative height difference orientations.

**i. Summary of Comparison for Varying Evaporator Angles Between 20 °C and 40 °C Coolant Inlet Temperatures at No Relative Height Difference.** An interesting difference between the two coolant temperatures for varying evaporator angles (Figures 4.1 and 4.2), is the initiation of a negative slope for some angular orientations at the 20 °C coolant inlet temperature. This negative slope region at the lower  $Q_{in}$  values appears to indicate a performance dependence upon operating temperature, since this phenomenon is observed only at the 20 °C coolant inlet temperature. Additionally, the formation of a negative slope region at the lower coolant inlet temperature appears to be related to the evaporator angular orientation. Thus, the evaporator angular influence becomes a factor only when the coolant is below some critical temperature. From Figure 4.2, the negative slope is clearly present at an evaporator angle of +135 degrees. If the uncertainty is neglected, the negative slope is present at 0 and -45 degrees as well.

Another difference observed between the two coolant temperatures for varying evaporator angles is that for the 40 °C coolant inlet temperature the LHP easily operates at the 15 watt  $Q_{in}$  for all angular orientations. While at the 20 °C temperature, only half of the angular orientations operated at this low of a  $Q_{in}$ . The evaporator angles at which the LHP successfully operated at 15 watts were: +135, 0, and -45 degrees, the same angles at which the negative slope is observed.

**ii. Summary for all Angular Orientations.** In comparing the  $\Delta T$  results between 40 °C and 20 °C for all the varying condenser and evaporator angular orientations, above 40 watts there doesn't appear to be a temperature influence on the  $\Delta T$ . However, below 40 watts at the 20 °C coolant inlet temperature, a negative slope region readily forms for both condenser and evaporator angular orientations.

## **B. Other Observations**

**1.  $Q_{in}$  Sensitivity.** The  $Q_{in}$  for each test was initially set high enough to insure LHP start up. Once started, the  $Q_{in}$  could then be reduced and the pipe would continue to operate. However, for a given  $\Delta H$  there appears to be a minimum  $Q_{in}$  required for LHP operation.

For many of the tests, keeping the LHP running at the lower  $Q_{in}$  values was often a rather delicate operation. LHP operation at the lower  $Q_{in}$  is sensitive to the rate at which the  $Q_{in}$  is decreased. The greater the  $Q_{in}$  step decrease, the greater the possibility that the LHP would become unstable and cease to operate. Unstable was defined as an evaporator temperature increase of 1 °C ~ 3 °C per minute for more than a few minutes. When the pipe was operating in the positive slope region it would easily handle up to a 15 watt step decrease between steady states. However, once the pipe was operating in the negative slope region, step decreases of 5 watts or less were used to insure continued operation.

**2. Observation of a  $\Delta T$  Anomaly.** There appears to be a point at which the slope either shifts from positive to negative or remains positive. This is referred to as a  $\Delta T$  anomaly.

This tendency for the pipe to continue to operate along the positive slope is clearly demonstrated in Figure 4.9 for tests 26 (0 degree condenser angle), and test 37, (+45 degree condenser angle). For test 26 where the condenser angle is horizontal,  $\Delta T$  continues to decrease with decreasing  $Q_{in}$  along the positive slope line. Additionally, for test 37 where the angle is +45 degrees, the 25 watt  $Q_{in}$  data point lies on a projection of its positive slope line.

Another test that demonstrates the  $\Delta T$  anomaly is test 44 (in which the condenser angle is set at +90 at a  $\Delta H$  of 1.22 meters, Figure 4.8). The pipe was started in the morning and allowed to stabilize for 90 minutes at 30 watts; it stabilized at a  $\Delta T$  of 1.09 °C. The data acquisition equipment locked up and so the test was reaccomplished for the 30 watt data point later that day. Again the LHP was allowed to stabilize for 90 minutes, however, this time the  $\Delta T$  was 6.42 °C. Plotting the first point of  $\Delta T$  of 1.09 °C at 30 watts places it on an extrapolated line drawn from the positive slope region for the +90 degree condenser plot of Figure 4.8.

**3. Evaporator Angle Performance Enhancement.** For the evaporator angular orientations which developed a negative slope, the  $\Delta T$  was significantly lower than for condenser angular orientations at the same  $\Delta H$  and  $Q_{in}$ . This is observed for a  $\Delta H$  of 1.22 meters, where evaporator angular orientations of -45, and -90 degrees operated at a  $Q_{in}$  of 15 watts at a  $\Delta T$  between 4.10 °C and 5.77 °C, where for the same  $\Delta H$  and  $Q_{in}$  the varying condenser angular orientations maintained a  $\Delta T$  between 12.71 °C and 15.42 °C (Figure 4.5 vs 4.8).

Thus it appears that there exist optimum evaporator angular orientations, in the negative slope region, which improve the performance of the loop heat pipe.

### **C. Performance Degradation**

#### **1. Observed Failure Modes.**

**i. Sensitivity to Decreases in Input Power.** As mentioned above, the LHP is sensitive to the rate of decrease of input power. Further, it appears that depending on the slope at which the LHP is operating (positive or negative) it is more or less sensitive to the step size decrease of power. The LHP is most sensitive to the rate of decrease when operating on the negative slope.

**ii. Minimum  $Q_{in}$  dependence on Evaporator Angles.** The LHP operated successfully at a  $Q_{in}$  as low as 15 watts for all condenser angular orientations at both 20 °C and 40 °C coolant inlet temperature. This was not the case for evaporator angular orientations. The LHP operated successfully at all evaporator angular orientations when the coolant inlet temperature was at 40 °C. However, when the coolant inlet temperature was 20 °C, the LHP did not operate consistently at a  $Q_{in}$  of 15 watts for all evaporator angles.

**2. Performance Degradation with  $\Delta H$ .** The LHP was found to operate at all condenser angular orientations for all heights at a  $Q_{in}$  minimum of 15 watts. However, depending on the height, the  $\Delta T$  at the  $Q_{in}$  minimum varied. The  $\Delta T$  at  $Q_{in}$  minimum of 15 watts was found to increase (decreasing performance) with increasing  $\Delta H$ .

## **V. Conclusions and Recommendations**

The focus of this research has been to determine the effects of varying angular orientation and height on the performance of a loop heat pipe (LHP). The tests performed have enabled the evaluation of LHP performance with respect to: varying evaporator angular orientation, varying condenser angular orientation, different coolant temperatures, and varying relative height difference ( $\Delta H$ ) for evaporator-over-condenser. The following is a summary of the conclusions drawn from this research, followed by recommendations for future work.

### **A. Conclusions**

**1. Performance Dependence on Evaporator Angle.** The LHP performance was found to be sensitive to the evaporator angle in two areas, the first being whether or not a negative slope region would form, and the second being the heat input ( $Q_{in}$ ) point at which this negative slope forms. The evaporator angle was found not to influence LHP performance once the  $Q_{in}$  was above the transition point (from negative to positive slope region).

**2. Performance Dependence on Condenser Angle.** The condenser angular orientations appear to have the most consistent effects on performance. Throughout all tests where the  $Q_{in}$  was above the transition point (the LHP operating in the positive slope region), the +45 degree angle was found to have the lowest  $\Delta T$  (best performance) and the -45 degree angle the highest  $\Delta T$  (poorest performance).

**3. Performance Dependence on Coolant Temperature.** The most significant influence that coolant temperature had on LHP performance was related to whether or not a negative slope region would form. It was found that for all condenser and evaporator angles, where there was no relative height difference, that at the 40 °C coolant inlet temperature no negative slope region would form, and thus the LHP would operate at the lowest  $\Delta T$  for the lower  $Q_{in}$  values. For all test at a 20 °C coolant inlet temperature a negative slope region formed.

**4. Performance Dependence on Relative Heights of Evaporator Over Condenser.** It was found that once the pipe was operating in the positive slope region that  $\Delta H$  had a negligible influence on performance. However, the transition point from negative to positive slope, was found to increase as  $\Delta H$  increased. This reveals that for an application with a sufficiently high  $Q_{in}$ , the relative height will not adversely influence the ability of the pipe to transport heat in a downward direction.

**5.  $Q_{in}$  Influences.** It was found that for some evaporator angular orientations, the LHP would not operate below some minimum  $Q_{in}$ . One of the more significant items of interest is the LHP's sensitivity to the rate at which  $Q_{in}$  is decreased. When the  $Q_{in}$  was decreased too rapidly, the LHP failed to operate. This sensitivity was found to be greater when the LHP was operating in the negative slope region.

This sensitivity to the rate of decrease in  $Q_{in}$ , and the minimum  $Q_{in}$  required for certain evaporator orientations make this LHP of limited use on aircraft where varying heat fluxes may be experienced.



## **B. Recommendations:**

**1. Continue Evaluation of the Sensitivity to Step Decreases in  $Q_{in}$ .** The pipe was found to be sensitive to the rate at which the heat input was decreased. In order to insure LHPs are suitable for aircraft applications, this sensitivity should be evaluated thoroughly enough to gain an understanding of what factors influence it.

**2. Evaluate Performance Dependence on Various Line Routings.** All of the testing done and the analysis above has assumed the influence of the line routing to be negligible. A recommendation for future work is to test for various line routing to isolate this influence. This could be accomplished by a series of no-relative-height-difference tests where the condenser and evaporator are drawn together on the mounting bar, causing the 'S' shape of the lines to extend vertically up and down (see Figure 2.1).

**3. Continue Evaluation of the  $\Delta T$  Anomaly.** For some of the test where the  $\Delta T$  anomaly was observed, it was noted the tests were the first of the day, and  $Q_{in}$  was at or below the negative to positive slope transition  $Q_{in}$ . In this situation the LHP started with a constant temperature throughout. This constant temperature throughout, may have an influence on the ability to operate the LHP in the positive slope region.

A recommendation for future work is to accomplish more tests starting with the LHP at a constant temperature throughout, and starting at a  $Q_{in}$  near the transition  $Q_{in}$ . The intent of these tests would be to determine the parameters which control the transition from the negative to positive slope. The goal would be to determine a means of

controlling the LHP to operate in the positive slope region at the low values of  $Q_{in}$ , where the performance would be improved (lower  $\Delta T$ ) for the lower  $Q_{in}$ .

## Appendix A: Loop Heat Pipe (LHP) Operation

### **A. The Loop heat LHP (Gernert & Weidner)**

In Figure A.1 the numbers on the Figure represent specific fluid states. Figure A.2 presents a pressure temperature diagram showing the fluid states of Figure A.1.

Point 1 represents the vapor pressure and temperature at the interface of vapor and liquid at the surface of the wick. The vapor is collected in a series of grooves and headers which feed into the vapor line at point 2. As the vapor flows through the passages it continues to heat up, increasing its temperature, thus becoming slightly superheated. The vapor then travels through the vapor line to the condenser, where it enters at point 3. The vapor then condenses and through gravity and/or capillary forces (capillary action due to the taper of the condenser) the liquid migrates to the end of the condenser at point 4. The condensate then enters the liquid return line at point 5.

The vapor pressure then forces the liquid back up through the liquid line into a reservoir section in the evaporator. The evaporator has reservoirs on both ends of the wick connected together through an annular section. This configuration enables liquid to completely surround the wick structure. Ideally the device is made self priming by controlling the volumes of the reservoirs, condenser, and the liquid and vapor lines.

The evaporator is built with the reservoirs on the ends, away from the heat source to ensure the liquid fed to the interior section of the wick remains subcooled. This geometry ensures that upon initial heating the vapor will form in the vapor passageway

and not in the liquid reservoirs. As the vapor forms it displaces the liquid out of the vapor

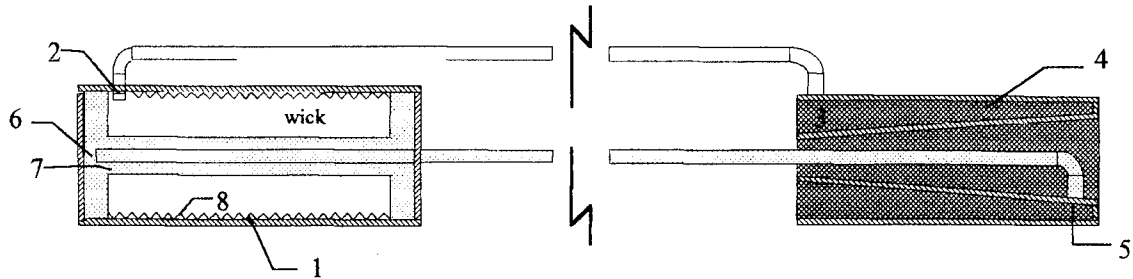


Figure A.1 Loop Heat Pipe

passageways and into the condenser where it is fed through the condenser liquid return line to the reservoirs in the evaporator. Ideally, the volumes and geometry are constructed such that should all the liquid be emptied out of the reservoirs then the liquid would saturate the wick through the vapor lines, thus insuring a self priming device.

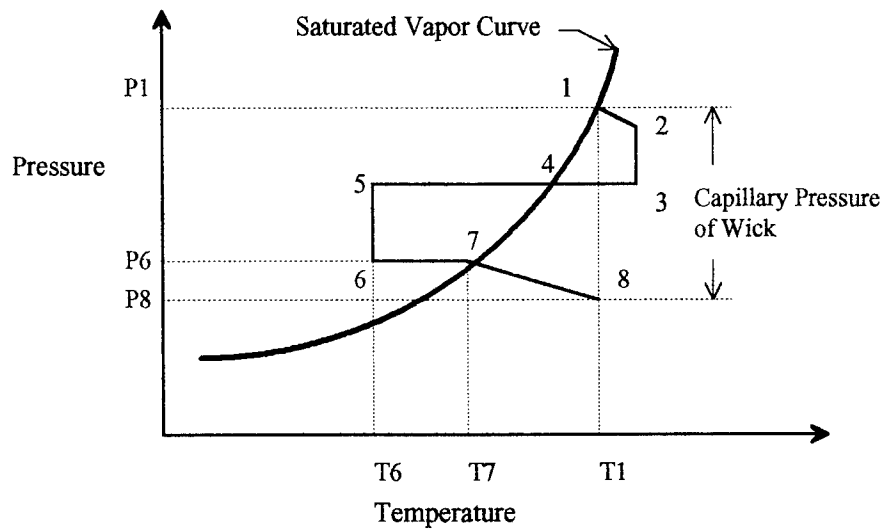


Figure A.2 Operating Cycle of a Loop Heat Pipe

Referencing Figure A.2, point 1 represents the vapor conditions on the wick just above the meniscus surface. The section from one to two (1-2) represents super heating of the vapor as it continues to flow through the vapor passages to the vapor header. The superheating is accompanied by a slight drop in pressure due to viscous forces acting on the vapor as it navigates the vapor passageways. The section from 2-3 represents an adiabatic transport of the vapor through the vapor line to the condenser, again the pressure drop is due to viscous forces acting on the vapor flow. The section from three to four (3-4) represents the vapor entering the condenser and condensing at the saturation pressure, as it condenses the liquid continues to subcool through to point five (5).

The segment from 5-6 represents the liquid returning to the evaporator through the liquid line. The process is represented as being isothermal. The majority of the pressure loss can be attributed to overcoming gravitational head. Section 6-7 represent heating of the liquid in the reservoirs and the wick annulus. Section 7-8 represents the temperature increase and pressure loss as the liquid flows through the wick structure. Point 8 represents the liquid at the surface of the meniscus (vs. point 1 which represents the vapor at the surface of the meniscus). Section 8-1 represents the capillary pressure increase.

In order for the loop heat LHP to operate the capillary pressure,  $P_c$ , must be greater than the pressure difference between 8 and 1.

$$\Delta P_c = \frac{2\sigma}{r_c} \geq P_1 - P_8 \quad \text{Eqn 1}$$

Where  $\sigma$  is the fluid's surface tension, and  $r_c$  is the effective pore radius of the wick structure.

## **Appendix B: Sample of Data Recorded**

The following pages show a typical spreadsheet which contains the data recorded. This is for Test 44, which had two different steady state operating points as mentioned in Chapter IV.

|    | A                        | B                  | C               | D          | E          | F          | G         | H          | I          | J          | K    |
|----|--------------------------|--------------------|-----------------|------------|------------|------------|-----------|------------|------------|------------|------|
| 1  | Test 44                  |                    | 0               | 1          | 2          | 3          | 5         | 6          | 35         | 36         | 37   |
| 2  | Test 44 Evap: Horizontal | Cond: +90 degrees, | bath temp: 20 C |            |            |            |           |            |            |            |      |
| 3  | Evap over Cond by 48 inc | Ambient            | Evap End        | Evap Start | Evap Block | Evap Block | Evap Adia | TC 22/Cond | TC 23/Cond | TC 24/Cond |      |
| 4  | 09-Aug-94                | 12:30:47           | 23.2            | 35.5       | 35.9       | 36.3       | 36.6      | 36.1       | 36.2       | 25.6       | 23.1 |
| 5  | 09-Aug-94                | 12:26:47           | 23.4            | 35.5       | 35.9       | 36.3       | 36.6      | 36         | 36.1       | 25.6       | 23.1 |
| 6  | 09-Aug-94                | 12:28:47           | 23.1            | 35.5       | 35.9       | 36.3       | 36.5      | 36         | 36.1       | 25.6       | 23.2 |
| 7  | 09-Aug-94                | 12:24:47           | 23.5            | 35.4       | 35.8       | 36.2       | 36.5      | 35.9       | 36         | 25.8       | 23.1 |
| 8  | 09-Aug-94                | 12:32:47           | 23              | 35.5       | 36         | 36.3       | 36.6      | 36.1       | 36.1       | 25.6       | 23.1 |
| 9  | 09-Aug-94                | 12:44:47           | 23.1            | 34.8       | 35.2       | 35.8       | 36.2      | 35.3       | 35.4       | 33         | 28   |
| 10 | 09-Aug-94                | 12:56:43           | 23.1            | 34.4       | 34.8       | 35.4       | 35.8      | 35         | 35.1       | 33         | 28.3 |
| 11 | 09-Aug-94                | 13:04:47           | 23.3            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 34.9       | 33         | 28.4 |
| 12 | 09-Aug-94                | 13:48:47           | 23.6            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 13 | 09-Aug-94                | 14:18:41           | 23.7            | 34.4       | 34.7       | 35.4       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 14 | 09-Aug-94                | 14:26:47           | 23.5            | 34.4       | 34.8       | 35.4       | 35.7      | 34.9       | 35         | 33.2       | 28.7 |
| 15 | 09-Aug-94                | 12:40:47           | 23.1            | 35         | 35.4       | 36         | 36.4      | 35.5       | 35.7       | 32.8       | 27.7 |
| 16 | 09-Aug-94                | 12:52:47           | 23.2            | 34.5       | 34.9       | 35.5       | 35.9      | 35         | 35.2       | 33         | 28.3 |
| 17 | 09-Aug-94                | 13:14:47           | 23.3            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.5 |
| 18 | 09-Aug-94                | 13:26:47           | 23.5            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.5 |
| 19 | 09-Aug-94                | 13:50:47           | 24.2            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 20 | 09-Aug-94                | 13:10:47           | 23.1            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.5 |
| 21 | 09-Aug-94                | 13:36:41           | 23.4            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 22 | 09-Aug-94                | 12:42:47           | 23.1            | 34.9       | 35.3       | 35.9       | 36.3      | 35.4       | 35.5       | 32.9       | 27.9 |
| 23 | 09-Aug-94                | 12:46:47           | 23.3            | 34.7       | 35.1       | 35.7       | 36.1      | 35.2       | 35.4       | 33         | 28.1 |
| 24 | 09-Aug-94                | 13:00:47           | 23.4            | 34.3       | 34.7       | 35.4       | 35.7      | 34.9       | 35         | 33         | 28.3 |
| 25 | 09-Aug-94                | 13:08:47           | 23.2            | 34.2       | 34.6       | 35.3       | 35.6      | 34.8       | 34.9       | 33         | 28.4 |
| 26 | 09-Aug-94                | 13:38:47           | 23.4            | 34.2       | 34.6       | 35.3       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 27 | 09-Aug-94                | 13:46:47           | 23.4            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 28 | 09-Aug-94                | 13:58:47           | 23.7            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 29 | 09-Aug-94                | 14:28:47           | 23.8            | 34.4       | 34.7       | 35.4       | 35.8      | 34.9       | 35.1       | 33.1       | 28.7 |
| 30 | 09-Aug-94                | 12:54:47           | 23.6            | 34.4       | 34.8       | 35.5       | 35.9      | 35         | 35.1       | 33         | 28.3 |
| 31 | 09-Aug-94                | 13:12:47           | 23.7            | 34.2       | 34.6       | 35.2       | 35.6      | 34.7       | 34.9       | 33         | 28.5 |
| 32 | 09-Aug-94                | 13:30:47           | 23.4            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 33 | 09-Aug-94                | 13:44:47           | 23.4            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 34 | 09-Aug-94                | 13:56:47           | 23.4            | 34.3       | 34.7       | 35.3       | 35.7      | 34.8       | 35         | 33         | 28.5 |
| 35 | 09-Aug-94                | 14:04:47           | 23.4            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 36 | 09-Aug-94                | 14:10:47           | 24              | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 37 | 09-Aug-94                | 14:32:47           | 23.8            | 34.4       | 34.8       | 35.4       | 35.8      | 34.9       | 35         | 33.2       | 28.7 |
| 38 | 09-Aug-94                | 14:12:41           | 23.4            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 39 | 09-Aug-94                | 12:48:47           | 23.1            | 34.6       | 35         | 35.6       | 36        | 35.1       | 35.3       | 33         | 28.2 |
| 40 | 09-Aug-94                | 13:02:47           | 23.2            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33         | 28.4 |
| 41 | 09-Aug-94                | 13:16:47           | 24.1            | 34.2       | 34.6       | 35.2       | 35.6      | 34.7       | 34.9       | 33         | 28.5 |
| 42 | 09-Aug-94                | 13:18:47           | 23.4            | 34.2       | 34.6       | 35.2       | 35.6      | 34.7       | 34.9       | 33         | 28.5 |
| 43 | 09-Aug-94                | 13:24:47           | 23.4            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.5 |
| 44 | 09-Aug-94                | 13:34:47           | 23.3            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 45 | 09-Aug-94                | 14:20:47           | 23.5            | 34.4       | 34.8       | 35.4       | 35.7      | 34.9       | 35         | 33.1       | 28.7 |
| 46 | 09-Aug-94                | 14:30:47           | 23.7            | 34.4       | 34.8       | 35.4       | 35.8      | 34.9       | 35         | 33.2       | 28.7 |
| 47 | 09-Aug-94                | 13:20:47           | 23.3            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 48 | 09-Aug-94                | 14:02:47           | 23.6            | 34.3       | 34.7       | 35.3       | 35.7      | 34.8       | 35         | 33.1       | 28.6 |
| 49 | 09-Aug-94                | 14:06:47           | 23.4            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 50 | 09-Aug-94                | 14:24:47           | 23.5            | 34.4       | 34.8       | 35.4       | 35.8      | 34.9       | 35.1       | 33.2       | 28.7 |
| 51 | 09-Aug-94                | 12:58:47           | 23.2            | 34.4       | 34.7       | 35.4       | 35.8      | 34.9       | 35         | 33         | 28.3 |
| 52 | 09-Aug-94                | 13:06:47           | 23.4            | 34.3       | 34.7       | 35.3       | 35.7      | 34.8       | 35         | 33         | 28.4 |
| 53 | 09-Aug-94                | 13:40:47           | 23.3            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33.1       | 28.6 |
| 54 | 09-Aug-94                | 13:42:47           | 23.6            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 55 | 09-Aug-94                | 13:54:47           | 23.6            | 34.3       | 34.7       | 35.3       | 35.7      | 34.8       | 35         | 33.1       | 28.6 |
| 56 | 09-Aug-94                | 14:14:41           | 23.5            | 34.3       | 34.8       | 35.4       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 57 | 09-Aug-94                | 14:22:47           | 23.6            | 34.4       | 34.8       | 35.4       | 35.8      | 34.9       | 35         | 33.2       | 28.7 |
| 58 | 09-Aug-94                | 12:50:41           | 23.2            | 34.5       | 34.9       | 35.6       | 35.9      | 35.1       | 35.2       | 33         | 28.2 |
| 59 | 09-Aug-94                | 13:22:47           | 23.3            | 34.2       | 34.6       | 35.2       | 35.6      | 34.7       | 34.9       | 33         | 28.5 |
| 60 | 09-Aug-94                | 13:28:41           | 23.5            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.5 |
| 61 | 09-Aug-94                | 13:32:47           | 23.8            | 34.2       | 34.6       | 35.2       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 62 | 09-Aug-94                | 14:08:47           | 23.6            | 34.3       | 34.7       | 35.3       | 35.7      | 34.8       | 35         | 33.1       | 28.7 |
| 63 | 09-Aug-94                | 13:52:47           | 23.8            | 34.3       | 34.7       | 35.3       | 35.6      | 34.8       | 34.9       | 33         | 28.6 |
| 64 | 09-Aug-94                | 14:00:47           | 23.6            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 65 | 09-Aug-94                | 14:16:41           | 23.5            | 34.3       | 34.7       | 35.3       | 35.7      | 34.9       | 35         | 33.1       | 28.6 |
| 66 | 09-Aug-94                | 14:34:47           | 23.5            | 34.4       | 34.8       | 35.4       | 35.8      | 34.9       | 35.1       | 33.2       | 28.7 |
| 67 | 08-Aug-94                | 16:21:31           | 24.2            | 35         | 35.3       | 36.2       | 36.7      | 35.5       | 35.7       | 34.6       | 34.7 |
| 68 | 08-Aug-94                | 16:19:31           | 23.6            | 35.5       | 35.7       | 36.5       | 37        | 35.9       | 36         | 34.9       | 34.9 |
| 69 | 08-Aug-94                | 16:39:31           | 23.5            | 33.4       | 34.4       | 35.3       | 35.7      | 34.6       | 34.8       | 33.7       | 33.9 |
| 70 | 08-Aug-94                | 16:23:31           | 23.5            | 34.7       | 35.1       | 36         | 36.5      | 35.3       | 35.5       | 34.4       | 34.5 |
| 71 | 08-Aug-94                | 16:41:31           | 23.5            | 33.4       | 34.4       | 35.3       | 35.7      | 34.8       | 34.9       | 33.7       | 33.9 |
| 72 | 08-Aug-94                | 16:37:25           | 23.6            | 33.3       | 34.4       | 35.3       | 35.7      | 34.6       | 34.8       | 33.7       | 33.9 |
| 73 | 08-Aug-94                | 16:17:31           | 23.9            | 35.7       | 36         | 36.9       | 37.4      | 36.2       | 36.4       | 35.2       | 35.2 |
| 74 | 08-Aug-94                | 16:33:31           | 23.8            | 33.4       | 34.3       | 35.2       | 35.6      | 34.6       | 34.8       | 33.7       | 33.8 |
| 75 | 08-Aug-94                | 16:31:31           | 24.1            | 33.6       | 34.3       | 35.3       | 35.7      | 34.6       | 34.8       | 33.7       | 33.9 |

| A  | L           | M           | N            | O            | P             | Q             | R       | S             | T              | U           |
|----|-------------|-------------|--------------|--------------|---------------|---------------|---------|---------------|----------------|-------------|
| 1  |             |             |              |              |               |               |         |               |                |             |
| 2  | 38          | 39          | 40           | 50           | 51            | 60            | 61      | 70            | 71             | 72          |
| 3  |             |             |              |              |               |               |         |               |                | Test 44     |
| 4  | TC 25/Condt | TC 26/Condt | TC 27/CoolIn | CoolIn Intrp | Coolout Intrp | Specific Heat | Density | Flow rate vol | Heater current | Qin (watts) |
| 5  | 22.3        | 22.3        | 20.205       | 20.799       | 21.571        | 4.1814        | 0.998   | 0.703         | 0.42           | 15.485      |
| 6  | 22.3        | 22.2        | 20.23        | 20.824       | 21.623        | 4.1813        | 0.998   | 0.709         | 0.42           | 15.521      |
| 7  | 22.4        | 22.3        | 20.22        | 20.814       | 21.641        | 4.1813        | 0.998   | 0.71          | 0.42           | 15.521      |
| 8  | 22.3        | 22.2        | 20.153       | 20.746       | 21.561        | 4.1814        | 0.998   | 0.718         | 0.42           | 15.557      |
| 9  | 22.4        | 22.3        | 20.244       | 20.837       | 21.61         | 4.1813        | 0.998   | 0.699         | 0.42           | 15.557      |
| 10 | 25.4        | 24.8        | 20.202       | 20.796       | 23.261        | 4.181         | 0.9978  | 0.71          | 0.59           | 30.469      |
| 11 | 25.6        | 25          | 20.221       | 20.815       | 23.513        | 4.1809        | 0.9977  | 0.713         | 0.59           | 30.57       |
| 12 | 26.7        | 25.1        | 20.244       | 20.838       | 23.387        | 4.1809        | 0.9977  | 0.703         | 0.59           | 30.57       |
| 13 | 25.8        | 25.2        | 20.275       | 20.869       | 23.258        | 4.181         | 0.9978  | 0.703         | 0.59           | 30.57       |
| 14 | 25.9        | 25.2        | 20.316       | 20.91        | 23.634        | 4.1809        | 0.9977  | 0.69          | 0.59           | 30.57       |
| 15 | 26          | 25.3        | 20.337       | 20.931       | 23.6          | 4.1809        | 0.9977  | 0.689         | 0.59           | 30.57       |
| 16 | 25.3        | 24.6        | 20.19        | 20.784       | 23.128        | 4.181         | 0.9978  | 0.728         | 0.59           | 30.662      |
| 17 | 25.6        | 24.9        | 20.221       | 20.815       | 23.277        | 4.181         | 0.9978  | 0.699         | 0.59           | 30.662      |
| 18 | 25.8        | 25.1        | 20.268       | 20.862       | 23.368        | 4.1809        | 0.9977  | 0.7           | 0.59           | 30.662      |
| 19 | 25.9        | 25.2        | 20.287       | 20.881       | 23.343        | 4.1809        | 0.9977  | 0.694         | 0.59           | 30.662      |
| 20 | 25.8        | 25.2        | 20.289       | 20.883       | 23.598        | 4.1809        | 0.9977  | 0.703         | 0.59           | 30.662      |
| 21 | 25.8        | 25.1        | 20.287       | 20.881       | 23.557        | 4.1809        | 0.9977  | 0.699         | 0.59           | 30.712      |
| 22 | 25.9        | 25.2        | 20.268       | 20.862       | 23.384        | 4.1809        | 0.9977  | 0.691         | 0.59           | 30.712      |
| 23 | 25.3        | 24.7        | 20.229       | 20.823       | 23.254        | 4.181         | 0.9978  | 0.725         | 0.59           | 30.763      |
| 24 | 25.5        | 24.8        | 20.214       | 20.808       | 23.342        | 4.1809        | 0.9978  | 0.703         | 0.59           | 30.763      |
| 25 | 25.7        | 25          | 20.217       | 20.811       | 23.448        | 4.1809        | 0.9977  | 0.71          | 0.59           | 30.763      |
| 26 | 25.7        | 25.1        | 20.264       | 20.857       | 23.376        | 4.1809        | 0.9977  | 0.699         | 0.59           | 30.763      |
| 27 | 25.9        | 25.2        | 20.295       | 20.889       | 23.6          | 4.1809        | 0.9977  | 0.689         | 0.59           | 30.763      |
| 28 | 25.9        | 25.2        | 20.278       | 20.872       | 23.513        | 4.1809        | 0.9977  | 0.71          | 0.59           | 30.763      |
| 29 | 25.9        | 25.2        | 20.284       | 20.878       | 23.492        | 4.1809        | 0.9977  | 0.7           | 0.59           | 30.763      |
| 30 | 26          | 25.3        | 20.321       | 20.915       | 23.449        | 4.1809        | 0.9977  | 0.689         | 0.59           | 30.763      |
| 31 | 25.8        | 25          | 20.26        | 20.854       | 23.471        | 4.1809        | 0.9977  | 0.713         | 0.59           | 30.814      |
| 32 | 25.8        | 25.1        | 20.253       | 20.847       | 23.309        | 4.1809        | 0.9978  | 0.7           | 0.59           | 30.814      |
| 33 | 25.8        | 25.2        | 20.287       | 20.881       | 23.472        | 4.1809        | 0.9977  | 0.689         | 0.59           | 30.814      |
| 34 | 25.9        | 25.2        | 20.263       | 20.857       | 23.273        | 4.181         | 0.9978  | 0.709         | 0.59           | 30.814      |
| 35 | 25.9        | 25.2        | 20.281       | 20.875       | 23.492        | 4.1809        | 0.9977  | 0.7           | 0.59           | 30.814      |
| 36 | 25.9        | 25.2        | 20.293       | 20.887       | 23.363        | 4.1809        | 0.9977  | 0.699         | 0.59           | 30.814      |
| 37 | 25.9        | 25.2        | 20.283       | 20.877       | 23.58         | 4.1809        | 0.9977  | 0.694         | 0.59           | 30.814      |
| 38 | 26          | 25.3        | 20.333       | 20.927       | 23.671        | 4.1808        | 0.9977  | 0.684         | 0.59           | 30.814      |
| 39 | 25.9        | 25.2        | 20.326       | 20.92        | 23.567        | 4.1809        | 0.9977  | 0.689         | 0.59           | 30.855      |
| 40 | 25.5        | 24.9        | 20.23        | 20.824       | 23.485        | 4.1809        | 0.9977  | 0.704         | 0.59           | 30.865      |
| 41 | 25.7        | 25          | 20.237       | 20.831       | 23.338        | 4.1809        | 0.9978  | 0.71          | 0.59           | 30.865      |
| 42 | 25.8        | 25.1        | 20.253       | 20.847       | 23.439        | 4.1809        | 0.9977  | 0.699         | 0.59           | 30.865      |
| 43 | 25.8        | 25.1        | 20.245       | 20.839       | 23.57         | 4.1809        | 0.9977  | 0.695         | 0.59           | 30.865      |
| 44 | 25.8        | 25.2        | 20.269       | 20.863       | 23.518        | 4.1809        | 0.9977  | 0.694         | 0.59           | 30.865      |
| 45 | 25.9        | 25.2        | 20.283       | 20.877       | 23.468        | 4.1809        | 0.9977  | 0.694         | 0.59           | 30.865      |
| 46 | 26          | 25.3        | 20.323       | 20.917       | 23.378        | 4.1809        | 0.9977  | 0.694         | 0.59           | 30.865      |
| 47 | 25.9        | 25.3        | 20.322       | 20.916       | 23.587        | 4.1809        | 0.9977  | 0.689         | 0.59           | 30.865      |
| 48 | 25.8        | 25.2        | 20.241       | 20.835       | 23.481        | 4.1809        | 0.9977  | 0.694         | 0.59           | 30.906      |
| 49 | 25.9        | 25.2        | 20.304       | 20.898       | 23.509        | 4.1809        | 0.9977  | 0.699         | 0.59           | 30.906      |
| 50 | 25.9        | 25.2        | 20.295       | 20.889       | 23.435        | 4.1809        | 0.9977  | 0.69          | 0.59           | 30.906      |
| 51 | 26          | 25.3        | 20.323       | 20.917       | 23.45         | 4.1809        | 0.9977  | 0.691         | 0.59           | 30.906      |
| 52 | 25.7        | 25          | 20.234       | 20.828       | 23.32         | 4.1809        | 0.9978  | 0.71          | 0.59           | 30.957      |
| 53 | 25.7        | 25.1        | 20.24        | 20.834       | 23.353        | 4.1809        | 0.9977  | 0.699         | 0.59           | 30.957      |
| 54 | 25.9        | 25.2        | 20.264       | 20.858       | 23.365        | 4.1809        | 0.9977  | 0.684         | 0.59           | 30.957      |
| 55 | 25.9        | 25.2        | 20.298       | 20.892       | 23.471        | 4.1809        | 0.9977  | 0.684         | 0.59           | 30.957      |
| 56 | 25.9        | 25.2        | 20.297       | 20.891       | 23.591        | 4.1809        | 0.9977  | 0.699         | 0.59           | 30.957      |
| 57 | 25.9        | 25.2        | 20.298       | 20.892       | 23.592        | 4.1809        | 0.9977  | 0.694         | 0.59           | 30.957      |
| 58 | 26          | 25.3        | 20.322       | 20.916       | 23.587        | 4.1809        | 0.9977  | 0.69          | 0.59           | 30.957      |
| 59 | 25.6        | 24.9        | 20.22        | 20.814       | 23.318        | 4.1809        | 0.9978  | 0.699         | 0.59           | 31.008      |
| 60 | 25.9        | 25.2        | 20.26        | 20.854       | 23.573        | 4.1809        | 0.9977  | 0.694         | 0.59           | 31.008      |
| 61 | 25.8        | 25.2        | 20.256       | 20.85        | 23.415        | 4.1809        | 0.9977  | 0.69          | 0.59           | 31.008      |
| 62 | 25.9        | 25.2        | 20.249       | 20.843       | 23.289        | 4.1809        | 0.9978  | 0.69          | 0.59           | 31.008      |
| 63 | 25.9        | 25.2        | 20.296       | 20.89        | 23.336        | 4.1809        | 0.9977  | 0.694         | 0.59           | 31.008      |
| 64 | 25.9        | 25.2        | 20.262       | 20.856       | 23.611        | 4.1809        | 0.9977  | 0.699         | 0.59           | 31.059      |
| 65 | 25.9        | 25.2        | 20.301       | 20.895       | 23.356        | 4.1809        | 0.9977  | 0.695         | 0.59           | 31.059      |
| 66 | 25.9        | 25.3        | 20.328       | 20.922       | 23.455        | 4.1809        | 0.9977  | 0.693         | 0.59           | 31.059      |
| 67 | 26          | 25.3        | 20.306       | 20.9         | 23.449        | 4.1809        | 0.9977  | 0.685         | 0.59           | 31.059      |
| 68 | 34.3        | 33.6        | 20.221       | 20.815       | 24.822        | 4.1806        | 0.9976  | 0.734         | 0.72           | 45.513      |
| 69 | 34.1        | 32.7        | 20.195       | 20.789       | 24.708        | 4.1806        | 0.9976  | 0.734         | 0.72           | 45.686      |
| 70 | 33.7        | 35          | 20.243       | 20.836       | 24.54         | 4.1807        | 0.9976  | 0.725         | 0.72           | 45.686      |
| 71 | 34.3        | 34.9        | 20.222       | 20.816       | 24.735        | 4.1806        | 0.9976  | 0.735         | 0.72           | 45.748      |
| 72 | 33.7        | 35          | 20.192       | 20.786       | 24.386        | 4.1807        | 0.9976  | 0.729         | 0.72           | 45.748      |
| 73 | 33.7        | 35          | 20.21        | 20.804       | 24.361        | 4.1807        | 0.9976  | 0.725         | 0.72           | 45.86       |
| 74 | 33.9        | 31.9        | 20.194       | 20.788       | 24.534        | 4.1807        | 0.9976  | 0.735         | 0.72           | 45.922      |
| 75 | 33.7        | 34.9        | 20.205       | 20.799       | 24.326        | 4.1807        | 0.9976  | 0.729         | 0.72           | 45.922      |
| 76 | 33.7        | 34.9        | 20.224       | 20.818       | 24.403        | 4.1807        | 0.9976  | 0.729         | 0.72           | 46.096      |



| A  | X       | Y         | Z       | AA            | AB        | AC      | AD       | AE       | AF      | AG          | AH            |
|----|---------|-----------|---------|---------------|-----------|---------|----------|----------|---------|-------------|---------------|
| 1  |         |           |         |               |           |         |          |          |         |             |               |
| 2  |         |           | 73      | 74            | 75        | 76      | 77       | 78       | 79      |             |               |
| 3  |         |           | Test 44 | Test 44       | Test 44   | Test 44 | Test 44  | Test 44  | Test 44 |             |               |
| 4  | Qin avg | Qin stdev | PM      | Heat Flow out | Heat loss | % loss  | Evap Avg | Cond Avg | Delta T | Delta T avg | Delta T stdev |
| 5  | 0       | 0         | 0.141   | 7.557         | 7.927     | 51.19   | 36.447   | 23.69    | 12.76   | 0           | 0             |
| 6  | 0       | 0         | 0.142   | 7.889         | 7.631     | 49.17   | 36.418   | 23.689   | 12.73   | 0           | 0             |
| 7  | 0       | 0         | 0.142   | 8.166         | 7.355     | 47.39   | 36.411   | 23.72    | 12.69   | 0           | 0             |
| 8  | 0       | 0         | 0.144   | 8.138         | 7.419     | 47.69   | 36.34    | 23.742   | 12.6    | 0           | 0             |
| 9  | 15.528  | 0.0301    | 0.14    | 7.514         | 8.043     | 51.7    | 36.463   | 23.694   | 12.77   | 12.709      | 0.0690036     |
| 10 | 0       | 0         | 0.142   | 24.329        | 6.14      | 20.15   | 35.993   | 28.788   | 7.205   | 0           | 0             |
| 11 | 0       | 0         | 0.143   | 26.745        | 3.825     | 12.51   | 35.611   | 28.968   | 6.643   | 0           | 0             |
| 12 | 0       | 0         | 0.141   | 24.933        | 5.637     | 18.44   | 35.525   | 29.024   | 6.501   | 0           | 0             |
| 13 | 0       | 0         | 0.141   | 23.37         | 7.201     | 23.55   | 35.419   | 29.153   | 6.266   | 0           | 0             |
| 14 | 0       | 0         | 0.138   | 26.135        | 4.435     | 14.51   | 35.555   | 29.212   | 6.343   | 0           | 0             |
| 15 | 0       | 0         | 0.138   | 25.585        | 4.985     | 16.31   | 35.55    | 29.279   | 6.271   | 0           | 0             |
| 16 | 0       | 0         | 0.146   | 23.742        | 6.92      | 22.57   | 36.201   | 28.609   | 7.592   | 0           | 0             |
| 17 | 0       | 0         | 0.14    | 23.939        | 6.722     | 21.92   | 35.691   | 28.961   | 6.73    | 0           | 0             |
| 18 | 0       | 0         | 0.14    | 24.399        | 6.263     | 20.43   | 35.408   | 29.089   | 6.319   | 0           | 0             |
| 19 | 0       | 0         | 0.139   | 23.74         | 6.922     | 22.58   | 35.425   | 29.123   | 6.302   | 0           | 0             |
| 20 | 0       | 0         | 0.141   | 26.555        | 4.107     | 13.39   | 35.434   | 29.155   | 6.279   | 0           | 0             |
| 21 | 0       | 0         | 0.14    | 26.022        | 4.69      | 15.27   | 35.43    | 29.085   | 6.344   | 0           | 0             |
| 22 | 0       | 0         | 0.138   | 24.22         | 6.492     | 21.14   | 35.431   | 29.185   | 6.246   | 0           | 0             |
| 23 | 0       | 0         | 0.145   | 24.508        | 6.255     | 20.33   | 36.081   | 28.694   | 7.387   | 0           | 0             |
| 24 | 0       | 0         | 0.141   | 24.769        | 5.994     | 19.48   | 35.902   | 28.858   | 7.044   | 0           | 0             |
| 25 | 0       | 0         | 0.142   | 26.028        | 4.735     | 15.39   | 35.543   | 28.987   | 6.556   | 0           | 0             |
| 26 | 0       | 0         | 0.14    | 24.495        | 6.268     | 20.37   | 35.451   | 29.039   | 6.412   | 0           | 0             |
| 27 | 0       | 0         | 0.138   | 25.992        | 4.771     | 15.51   | 35.442   | 29.162   | 6.28    | 0           | 0             |
| 28 | 0       | 0         | 0.142   | 26.066        | 4.697     | 15.27   | 35.423   | 29.167   | 6.256   | 0           | 0             |
| 29 | 0       | 0         | 0.14    | 25.442        | 5.321     | 17.3    | 35.501   | 29.171   | 6.33    | 0           | 0             |
| 30 | 0       | 0         | 0.138   | 24.291        | 6.472     | 21.04   | 35.562   | 29.274   | 6.288   | 0           | 0             |
| 31 | 0       | 0         | 0.143   | 25.961        | 4.853     | 15.75   | 35.654   | 28.989   | 6.665   | 0           | 0             |
| 32 | 0       | 0         | 0.14    | 23.959        | 6.855     | 22.25   | 35.405   | 29.1     | 6.304   | 0           | 0             |
| 33 | 0       | 0         | 0.138   | 24.832        | 5.982     | 19.41   | 35.408   | 29.152   | 6.256   | 0           | 0             |
| 34 | 0       | 0         | 0.142   | 23.829        | 6.985     | 22.67   | 35.422   | 29.161   | 6.26    | 0           | 0             |
| 35 | 0       | 0         | 0.14    | 25.472        | 5.342     | 17.34   | 35.486   | 29.15    | 6.335   | 0           | 0             |
| 36 | 0       | 0         | 0.14    | 24.083        | 6.731     | 21.85   | 35.494   | 29.207   | 6.287   | 0           | 0             |
| 37 | 0       | 0         | 0.139   | 26.083        | 4.731     | 15.35   | 35.512   | 29.219   | 6.293   | 0           | 0             |
| 38 | 0       | 0         | 0.137   | 26.117        | 4.697     | 15.24   | 35.572   | 29.278   | 6.295   | 0           | 0             |
| 39 | 0       | 0         | 0.138   | 25.377        | 5.478     | 17.75   | 35.512   | 29.215   | 6.297   | 0           | 0             |
| 40 | 0       | 0         | 0.141   | 26.047        | 4.818     | 15.61   | 35.819   | 28.906   | 6.914   | 0           | 0             |
| 41 | 0       | 0         | 0.142   | 24.745        | 6.12      | 19.83   | 35.518   | 29.025   | 6.493   | 0           | 0             |
| 42 | 0       | 0         | 0.14    | 25.201        | 5.664     | 18.35   | 35.387   | 29.089   | 6.298   | 0           | 0             |
| 43 | 0       | 0         | 0.139   | 26.385        | 4.48      | 14.51   | 35.372   | 29.108   | 6.264   | 0           | 0             |
| 44 | 0       | 0         | 0.139   | 25.627        | 5.238     | 16.97   | 35.409   | 29.118   | 6.291   | 0           | 0             |
| 45 | 0       | 0         | 0.139   | 25.005        | 5.86      | 18.99   | 35.408   | 29.179   | 6.229   | 0           | 0             |
| 46 | 0       | 0         | 0.139   | 23.738        | 7.127     | 23.09   | 35.552   | 29.252   | 6.23    | 0           | 0             |
| 47 | 0       | 0         | 0.138   | 25.606        | 5.259     | 17.04   | 35.569   | 29.261   | 6.308   | 0           | 0             |
| 48 | 0       | 0         | 0.139   | 25.522        | 5.384     | 17.42   | 35.397   | 29.122   | 6.274   | 0           | 0             |
| 49 | 0       | 0         | 0.14    | 25.392        | 5.513     | 17.84   | 35.512   | 29.191   | 6.321   | 0           | 0             |
| 50 | 0       | 0         | 0.138   | 24.43         | 6.476     | 20.95   | 35.499   | 29.221   | 6.278   | 0           | 0             |
| 51 | 0       | 0         | 0.138   | 24.334        | 6.572     | 21.26   | 35.559   | 29.291   | 6.268   | 0           | 0             |
| 52 | 0       | 0         | 0.142   | 24.596        | 6.36      | 20.55   | 35.559   | 28.984   | 6.576   | 0           | 0             |
| 53 | 0       | 0         | 0.14    | 24.496        | 6.46      | 20.87   | 35.49    | 29.02    | 6.47    | 0           | 0             |
| 54 | 0       | 0         | 0.137   | 23.833        | 7.124     | 23.01   | 35.43    | 29.18    | 6.25    | 0           | 0             |
| 55 | 0       | 0         | 0.137   | 24.512        | 6.445     | 20.82   | 35.44    | 29.182   | 6.258   | 0           | 0             |
| 56 | 0       | 0         | 0.14    | 26.261        | 4.695     | 15.17   | 35.479   | 29.161   | 6.318   | 0           | 0             |
| 57 | 0       | 0         | 0.139   | 26.044        | 4.913     | 15.87   | 35.555   | 29.221   | 6.334   | 0           | 0             |
| 58 | 0       | 0         | 0.138   | 25.628        | 5.329     | 17.21   | 35.559   | 29.262   | 6.297   | 0           | 0             |
| 59 | 0       | 0         | 0.14    | 24.351        | 6.657     | 21.47   | 35.747   | 28.938   | 6.809   | 0           | 0             |
| 60 | 0       | 0         | 0.139   | 26.24         | 4.767     | 15.38   | 35.396   | 29.127   | 6.269   | 0           | 0             |
| 61 | 0       | 0         | 0.138   | 24.605        | 6.402     | 20.65   | 35.421   | 29.108   | 6.314   | 0           | 0             |
| 62 | 0       | 0         | 0.138   | 23.475        | 7.532     | 24.29   | 35.413   | 29.169   | 6.244   | 0           | 0             |
| 63 | 0       | 0         | 0.139   | 23.61         | 7.397     | 23.86   | 35.504   | 29.223   | 6.282   | 0           | 0             |
| 64 | 0       | 0         | 0.14    | 26.789        | 4.269     | 13.75   | 35.454   | 29.183   | 6.272   | 0           | 0             |
| 65 | 0       | 0         | 0.139   | 23.777        | 7.282     | 23.45   | 35.535   | 29.163   | 6.371   | 0           | 0             |
| 66 | 0       | 0         | 0.139   | 24.415        | 6.644     | 21.39   | 35.539   | 29.231   | 6.309   | 0           | 0             |
| 67 | 30.828  | 0.1445    | 0.137   | 24.294        | 6.765     | 21.78   | 35.587   | 29.263   | 6.323   | 6.42276     | 0.28794       |
| 68 | 0       | 0         | 0.147   | 40.904        | 4.609     | 10.13   | 36.438   | 34.539   | 1.897   | 0           | 0             |
| 69 | 0       | 0         | 0.147   | 40.005        | 5.681     | 12.43   | 36.767   | 34.66    | 2.107   | 0           | 0             |
| 70 | 0       | 0         | 0.145   | 37.326        | 8.36      | 18.3    | 35.489   | 33.79    | 1.698   | 0           | 0             |
| 71 | 0       | 0         | 0.147   | 40.032        | 5.716     | 12.5    | 36.221   | 34.426   | 1.795   | 0           | 0             |
| 72 | 0       | 0         | 0.146   | 36.486        | 9.262     | 20.25   | 35.519   | 33.801   | 1.719   | 0           | 0             |
| 73 | 0       | 0         | 0.145   | 35.866        | 10.004    | 21.81   | 35.501   | 33.783   | 1.718   | 0           | 0             |
| 74 | 0       | 0         | 0.147   | 38.263        | 7.659     | 16.68   | 37.146   | 34.765   | 2.381   | 0           | 0             |
| 75 | 0       | 0         | 0.146   | 35.747        | 10.175    | 22.16   | 35.447   | 33.756   | 1.691   | 0           | 0             |
| 76 | 0       | 0         | 0.146   | 36.332        | 9.763     | 21.18   | 35.459   | 33.756   | 1.703   | 0           | 0             |

| A   | B         | C                | D                 | E             | F          | G          | H          | I         | J          | K          |            |
|-----|-----------|------------------|-------------------|---------------|------------|------------|------------|-----------|------------|------------|------------|
| 1   | Test 44   |                  |                   |               |            |            |            |           |            |            |            |
| 2   |           | 0                | 1                 | 2             | 3          | 5          | 6          | 35        | 36         | 37         |            |
| 3   | Test 44   | Evap: Horizontal | Cond: +90 degrees | bath temp: 20 | C          |            |            |           | 35         |            |            |
| 4   | Evap over | Cond by 48 inc   | Ambient           | Evap End      | Evap Start | Evap Block | Evap Block | Evap Adia | TC 22/Cond | TC 23/Cond | TC 24/Cond |
| 77  | 08-Aug-94 | 16:35:31         | 23.3              | 33.5          | 34.4       | 35.3       | 35.7       | 34.6      | 34.8       | 33.7       | 33.9       |
| 78  | 08-Aug-94 | 16:05:31         | 23.8              | 38.1          | 38.7       | 39.7       | 40.3       | 38.9      | 39.1       | 37.5       | 37.7       |
| 79  | 08-Aug-94 | 16:01:31         | 23.3              | 38.4          | 38.8       | 39.8       | 40.4       | 39        | 39.2       | 37.6       | 37.9       |
| 80  | 08-Aug-94 | 15:59:25         | 23.4              | 38.3          | 38.9       | 39.9       | 40.5       | 39        | 39.2       | 37.7       | 37.9       |
| 81  | 08-Aug-94 | 16:03:31         | 23.3              | 38.3          | 38.7       | 39.8       | 40.3       | 38.9      | 39.1       | 37.6       | 37.8       |
| 82  | 08-Aug-94 | 15:57:31         | 23.4              | 38.4          | 39         | 40         | 40.6       | 39.2      | 39.3       | 37.8       | 38         |
| 83  | 08-Aug-94 | 15:45:31         | 23.4              | 41.9          | 42.8       | 44.2       | 44.9       | 43        | 43.2       | 41.1       | 41.4       |
| 84  | 08-Aug-94 | 15:39:31         | 23.6              | 42.2          | 43         | 44.3       | 45         | 43.2      | 43.3       | 41.3       | 41.5       |
| 85  | 08-Aug-94 | 15:43:31         | 23.4              | 41.9          | 42.8       | 44.2       | 44.9       | 43.1      | 43.2       | 41.2       | 41.4       |
| 86  | 08-Aug-94 | 15:41:31         | 23.4              | 42.1          | 42.9       | 44.3       | 44.9       | 43.1      | 43.3       | 41.2       | 41.5       |
| 87  | 08-Aug-94 | 15:37:31         | 23.5              | 42.3          | 43.1       | 44.4       | 45.1       | 43.2      | 43.4       | 41.4       | 41.6       |
| 88  | 08-Aug-94 | 15:21:31         | 23.7              | 45.7          | 46.9       | 48.5       | 49.3       | 47.1      | 47.2       | 44.6       | 44.9       |
| 89  | 08-Aug-94 | 15:19:31         | 23.4              | 45.8          | 47         | 48.6       | 49.4       | 47.2      | 47.3       | 44.7       | 45         |
| 90  | 08-Aug-94 | 15:23:31         | 23.3              | 45.6          | 46.8       | 48.4       | 49.2       | 47        | 47.2       | 44.6       | 44.9       |
| 91  | 08-Aug-94 | 15:17:31         | 23.3              | 46.1          | 47.1       | 48.7       | 49.4       | 47.2      | 47.4       | 44.8       | 45.1       |
| 92  | 08-Aug-94 | 15:25:31         | 23.5              | 45.6          | 46.8       | 48.4       | 49.2       | 47        | 47.1       | 44.5       | 44.8       |
| 93  | 08-Aug-94 | 14:55:31         | 23.2              | 49.5          | 50.9       | 52.7       | 53.6       | 51        | 51.1       | 47.9       | 48.3       |
| 94  | 08-Aug-94 | 15:01:31         | 23.1              | 49.3          | 50.7       | 52.6       | 53.5       | 50.9      | 51         | 47.8       | 48.2       |
| 95  | 08-Aug-94 | 15:03:31         | 23.4              | 49.3          | 50.7       | 52.6       | 53.5       | 50.9      | 51         | 47.8       | 48.2       |
| 96  | 08-Aug-94 | 14:57:25         | 23.4              | 49.4          | 50.8       | 52.6       | 53.5       | 51        | 51.1       | 47.8       | 48.2       |
| 97  | 08-Aug-94 | 14:59:31         | 23.7              | 49.3          | 50.7       | 52.6       | 53.5       | 50.9      | 51.1       | 47.8       | 48.2       |
| 98  | 08-Aug-94 | 15:05:31         | 23.3              | 49.2          | 50.7       | 52.6       | 53.5       | 50.9      | 51         | 47.8       | 48.2       |
| 99  | 08-Aug-94 | 14:33:31         | 23.1              | 53.3          | 55.1       | 57.2       | 58.2       | 55.2      | 55.3       | 51.4       | 51.9       |
| 100 | 08-Aug-94 | 14:27:31         | 23.1              | 53            | 54.8       | 56.9       | 57.9       | 55        | 55.1       | 51.2       | 51.7       |
| 101 | 08-Aug-94 | 14:29:31         | 23.1              | 53.1          | 54.9       | 57         | 58         | 55.1      | 55.2       | 51.3       | 51.8       |
| 102 | 08-Aug-94 | 14:37:31         | 23.2              | 53.4          | 55.1       | 57.3       | 58.3       | 55.3      | 55.5       | 51.5       | 52.1       |
| 103 | 08-Aug-94 | 14:31:31         | 23                | 53.2          | 55         | 57.1       | 58.1       | 55.2      | 55.2       | 51.3       | 51.9       |
| 104 | 08-Aug-94 | 14:35:31         | 23.2              | 53.3          | 55.1       | 57.2       | 58.2       | 55.3      | 55.3       | 51.5       | 52         |
| 105 | 08-Aug-94 | 14:25:31         | 23.1              | 52.9          | 54.7       | 56.9       | 57.8       | 54.9      | 55         | 51.2       | 51.7       |
| 106 | 08-Aug-94 | 14:39:31         | 23.5              | 53.5          | 55.2       | 57.4       | 58.3       | 55.4      | 55.5       | 51.6       | 52.1       |
| 107 |           |                  |                   |               |            |            |            |           |            |            |            |
| 108 | 08-Aug-94 | 10:23:00         |                   |               |            |            |            |           |            |            |            |
| 109 | 08-Aug-94 | 10:25:00         |                   |               |            |            |            |           |            |            |            |
| 110 | 08-Aug-94 | 10:27:00         |                   |               |            |            |            |           |            |            |            |
| 111 | 08-Aug-94 | 10:29:00         |                   |               |            |            |            |           |            |            |            |
| 112 | 08-Aug-94 | 10:31:00         |                   |               |            |            |            |           |            |            |            |

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|  | L          | M          | N          | O           | P            | Q             | R       | S                     | T              | U           |
|--|------------|------------|------------|-------------|--------------|---------------|---------|-----------------------|----------------|-------------|
|  | 38         | 39         | 40         | 50          | 51           | 60            | 61      | 70                    | 71             | 72          |
|  |            |            |            |             |              |               |         |                       |                | Test 44     |
|  | TC 25/Cond | TC 26/Cond | TC 27/Cool | CoolIn Intp | Coolout Intp | Specific Heat | Density | Flow rate vol         | Heater current | Qin (watts) |
|  | 33.7       | 34.9       | 20.217     | 20.811      | 24.526       | 4.1807        | 0.9976  | 0.728                 | 0.72           | 46.096      |
|  | 37.6       | 39.2       | 20.208     | 20.802      | 25.432       | 4.1805        | 0.9975  | 0.739                 | 0.83           | 60.589      |
|  | 37.6       | 39.3       | 20.197     | 20.791      | 25.406       | 4.1805        | 0.9975  | 0.739                 | 0.83           | 60.646      |
|  | 37.7       | 39.4       | 20.212     | 20.806      | 25.42        | 4.1805        | 0.9975  | 0.739                 | 0.83           | 60.861      |
|  | 37.6       | 39.2       | 20.2       | 20.793      | 25.68        | 4.1804        | 0.9975  | 0.738                 | 0.83           | 61.133      |
|  | 37.8       | 39.5       | 20.165     | 20.759      | 25.373       | 4.1805        | 0.9975  | 0.738                 | 0.83           | 61.262      |
|  | 41.2       | 43.3       | 20.176     | 20.77       | 26.492       | 4.1802        | 0.9974  | 0.745                 | 0.92           | 75.365      |
|  | 41.3       | 43.5       | 20.191     | 20.784      | 26.566       | 4.1802        | 0.9974  | 0.748                 | 0.93           | 75.588      |
|  | 41.3       | 43.4       | 20.187     | 20.781      | 26.389       | 4.1803        | 0.9974  | 0.745                 | 0.93           | 75.811      |
|  | 41.3       | 43.4       | 20.186     | 20.78       | 26.207       | 4.1803        | 0.9974  | 0.745                 | 0.93           | 75.971      |
|  | 41.4       | 43.6       | 20.189     | 20.782      | 26.364       | 4.1803        | 0.9974  | 0.748                 | 0.93           | 76.194      |
|  | 44.7       | 47.4       | 20.166     | 20.759      | 27.45        | 4.18          | 0.9973  | 0.76                  | 1.01           | 90.491      |
|  | 44.9       | 47.4       | 20.202     | 20.796      | 27.768       | 4.1799        | 0.9972  | 0.754                 | 1.01           | 90.578      |
|  | 44.7       | 47.3       | 20.187     | 20.78       | 27.414       | 4.18          | 0.9973  | 0.754                 | 1.01           | 90.578      |
|  | 44.8       | 47.5       | 20.167     | 20.761      | 27.609       | 4.18          | 0.9973  | 0.76                  | 1.01           | 90.665      |
|  | 44.6       | 47.3       | 20.192     | 20.785      | 27.106       | 4.1801        | 0.9973  | 0.749                 | 1.01           | 90.752      |
|  | 48         | 51.3       | 20.166     | 20.76       | 28.401       | 4.1798        | 0.9972  | 0.764                 | 1.09           | 105.3       |
|  | 47.9       | 51.2       | 20.145     | 20.738      | 28.125       | 4.1799        | 0.9972  | 0.764                 | 1.09           | 105.3       |
|  | 47.9       | 51.2       | 20.138     | 20.732      | 28.106       | 4.1799        | 0.9972  | 0.76                  | 1.09           | 105.47      |
|  | 48         | 51.2       | 20.148     | 20.742      | 28.613       | 4.1797        | 0.9971  | 0.764                 | 1.09           | 105.56      |
|  | 48         | 51.2       | 20.181     | 20.775      | 28.431       | 4.1798        | 0.9972  | 0.764                 | 1.09           | 105.56      |
|  | 47.9       | 51.2       | 20.174     | 20.768      | 28.213       | 4.1798        | 0.9972  | 0.755                 | 1.1            | 105.85      |
|  | 51.7       | 55.5       | 20.201     | 20.795      | 30.119       | 4.1795        | 0.9969  | 0.719                 | 1.17           | 120.26      |
|  | 51.4       | 55.2       | 20.228     | 20.822      | 29.598       | 4.1796        | 0.997   | 0.735                 | 1.17           | 120.64      |
|  | 51.5       | 55.3       | 20.222     | 20.816      | 29.506       | 4.1796        | 0.997   | 0.729                 | 1.17           | 120.83      |
|  | 51.8       | 55.6       | 20.222     | 20.816      | 30.099       | 4.1795        | 0.9969  | 0.71                  | 1.17           | 120.93      |
|  | 51.6       | 55.4       | 20.211     | 20.805      | 29.664       | 4.1796        | 0.997   | 0.725                 | 1.17           | 121.03      |
|  | 51.8       | 55.6       | 20.248     | 20.842      | 30.165       | 4.1795        | 0.9969  | 0.719                 | 1.17           | 121.03      |
|  | 51.4       | 55.2       | 20.254     | 20.848      | 29.834       | 4.1796        | 0.997   | 0.748                 | 1.17           | 121.13      |
|  | 51.9       | 55.7       | 20.227     | 20.82       | 30.189       | 4.1795        | 0.9969  | 0.704                 | 1.17           | 121.61      |
|  |            |            |            |             |              |               |         |                       |                |             |
|  |            |            |            |             |              |               |         | From the earlier test |                | 30.4        |
|  |            |            |            |             |              |               |         |                       |                | 30.4        |
|  |            |            |            |             |              |               |         |                       |                | 30.5        |
|  |            |            |            |             |              |               |         |                       |                | 30.6        |
|  |            |            |            |             |              |               |         |                       |                | 30.4        |

| A   | X       | Y         | Z       | AA            | AB        | AC      | AD       | AE       | AF      | AG          | AH            |
|-----|---------|-----------|---------|---------------|-----------|---------|----------|----------|---------|-------------|---------------|
| 1   |         |           |         |               |           |         |          |          |         |             |               |
| 2   |         |           | 73      | 74            | 75        | 76      | 77       | 78       | 79      |             |               |
| 3   |         |           | Test 44 | Test 44       | Test 44   | Test 44 | Test 44  | Test 44  | Test 44 |             |               |
| 4   | Qin avg | Qin stdev | PM      | Heat Flow out | Heat loss | % loss  | Evap Avg | Cond Avg | Delta T | Delta T avg | Delta T stdev |
| 77  | 45.828  | 0.187     | 0.146   | 37.593        | 8.502     | 18.44   | 35.473   | 33.784   | 1.689   | 1.8398      | 0.2315896     |
| 78  | 0       | 0         | 0.148   | 47.549        | 13.04     | 21.52   | 40.026   | 37.6     | 2.426   | 0           | 0             |
| 79  | 0       | 0         | 0.148   | 47.396        | 13.251    | 21.85   | 40.109   | 37.71    | 2.399   | 0           | 0             |
| 80  | 0       | 0         | 0.148   | 47.395        | 13.466    | 22.13   | 40.188   | 37.778   | 2.409   | 0           | 0             |
| 81  | 0       | 0         | 0.148   | 50.145        | 10.988    | 17.97   | 40.055   | 37.634   | 2.421   | 0           | 0             |
| 82  | 60.898  | 0.295     | 0.148   | 47.357        | 13.905    | 22.7    | 40.325   | 37.864   | 2.461   | 2.4232      | 0.0236051     |
| 83  | 0       | 0         | 0.149   | 59.218        | 16.146    | 21.42   | 44.528   | 41.241   | 3.287   | 0           | 0             |
| 84  | 0       | 0         | 0.15    | 60.116        | 15.471    | 20.47   | 44.646   | 41.373   | 3.273   | 0           | 0             |
| 85  | 0       | 0         | 0.149   | 58.045        | 17.766    | 23.43   | 44.529   | 41.285   | 3.244   | 0           | 0             |
| 86  | 0       | 0         | 0.149   | 56.21         | 19.76     | 26.01   | 44.583   | 41.328   | 3.255   | 0           | 0             |
| 87  | 75.786  | 0.3232    | 0.15    | 58.042        | 18.153    | 23.82   | 44.742   | 41.432   | 3.31    | 3.2738      | 0.0261094     |
| 88  | 0       | 0         | 0.152   | 70.678        | 19.813    | 21.89   | 48.886   | 44.757   | 4.129   | 0           | 0             |
| 89  | 0       | 0         | 0.151   | 73.036        | 17.542    | 19.37   | 48.958   | 44.85    | 4.109   | 0           | 0             |
| 90  | 0       | 0         | 0.151   | 69.492        | 21.086    | 23.28   | 48.84    | 44.71    | 4.13    | 0           | 0             |
| 91  | 0       | 0         | 0.152   | 72.341        | 18.324    | 20.21   | 49.049   | 44.881   | 4.168   | 0           | 0             |
| 92  | 90.613  | 0.0992    | 0.15    | 65.759        | 24.993    | 27.54   | 48.788   | 44.638   | 4.15    | 4.1372      | 0.02251       |
| 93  | 0       | 0         | 0.153   | 81.153        | 24.146    | 22.93   | 53.145   | 48.075   | 5.07    | 0           | 0             |
| 94  | 0       | 0         | 0.153   | 78.387        | 26.912    | 25.56   | 53.031   | 47.952   | 5.078   | 0           | 0             |
| 95  | 0       | 0         | 0.152   | 77.9          | 27.569    | 26.14   | 53.028   | 47.955   | 5.073   | 0           | 0             |
| 96  | 0       | 0         | 0.153   | 83.515        | 22.047    | 20.89   | 53.09    | 48.01    | 5.079   | 0           | 0             |
| 97  | 0       | 0         | 0.153   | 81.242        | 24.321    | 23.04   | 53.046   | 47.985   | 5.061   | 0           | 0             |
| 98  | 105.51  | 0.2051    | 0.151   | 78.1          | 27.745    | 26.21   | 53.006   | 47.958   | 5.049   | 5.06833     | 0.0114833     |
| 99  | 0       | 0         | 0.144   | 93.13         | 27.132    | 22.56   | 57.685   | 51.686   | 5.999   | 0           | 0             |
| 100 | 0       | 0         | 0.147   | 89.565        | 31.079    | 25.76   | 57.381   | 51.452   | 5.929   | 0           | 0             |
| 101 | 0       | 0         | 0.146   | 87.984        | 32.842    | 27.18   | 57.483   | 51.518   | 5.964   | 0           | 0             |
| 102 | 0       | 0         | 0.142   | 91.499        | 29.427    | 24.33   | 57.771   | 51.809   | 5.962   | 0           | 0             |
| 103 | 0       | 0         | 0.145   | 89.198        | 31.829    | 26.3    | 57.587   | 51.603   | 5.984   | 0           | 0             |
| 104 | 0       | 0         | 0.144   | 93.117        | 27.91     | 23.06   | 57.719   | 51.733   | 5.986   | 0           | 0             |
| 105 | 0       | 0         | 0.15    | 93.361        | 27.767    | 22.92   | 57.334   | 51.418   | 5.916   | 0           | 0             |
| 106 | 120.93  | 0.3901    | 0.141   | 91.596        | 30.017    | 24.68   | 57.854   | 51.852   | 6.002   | 5.96775     | 0.0315629     |
| 107 |         |           |         |               |           |         |          |          |         |             |               |
| 108 |         |           | 0.148   | 24.1          | 6.3       | 20.72%  | 30.62    | 29.52    | 1.1     |             |               |
| 109 |         |           | 0.148   | 24.2          | 6.2       | 20.39%  | 30.62    | 29.51    | 1.11    |             |               |
| 110 |         |           | 0.147   | 24.3          | 6.2       | 20.33%  | 30.63    | 29.52    | 1.11    |             |               |
| 111 |         |           | 0.147   | 25            | 5.6       | 18.30%  | 30.62    | 29.54    | 1.08    |             |               |
| 112 | 30.46   | 0.08      | 0.147   | 25.4          | 5         | 16.45%  | 30.61    | 29.54    | 1.07    | 1.094       | 0.0063246     |

## Appendix C: Uncertainty Calculations

Uncertainty calculations for  $\Delta T$ :

$$\Delta T = \frac{tc3 + tc5}{2} - \frac{tc36 + tc37 + tc38}{2} \quad tc = \text{thermocouple}$$

$$d\Delta T = \left| \left( \frac{d}{d tc3} \Delta T \right) \cdot \delta tc3 \right| + \left| \left( \frac{d}{d tc5} \Delta T \right) \cdot \delta tc5 \right| + \left| \left( \frac{d}{d tc36} \Delta T \right) \cdot \delta tc36 \right| + \left| \left( \frac{d}{d tc37} \Delta T \right) \cdot \delta tc37 \right| + \left| \left( \frac{d}{d tc38} \Delta T \right) \cdot \delta tc38 \right| \dots$$

$$d\Delta T = \left| \frac{1}{2} \cdot \delta tc3 \right| + \left| \frac{1}{2} \cdot \delta tc5 \right| + \left| \frac{1}{3} \cdot \delta tc36 \right| + \left| \frac{1}{3} \cdot \delta tc37 \right| + \left| \frac{1}{3} \cdot \delta tc38 \right|$$

The estimate in the uncertainty for the thermocouple temperature measured using the Fluke data logger is, according to the Fluke specifications,  $\pm 0.65 \text{ }^\circ\text{C}$ . This is the uncertainty then for all thermocouple temperatures.

$$\delta tc3 = \delta tc5 = \delta tc36 = \delta tc37 = \delta tc38 = \delta tc$$

Thus we have:  $d\Delta T = 2 \cdot \delta tc = 2 \cdot 0.65 \text{ }^\circ\text{C} = 1.3 \text{ }^\circ\text{C}$

$$\Delta T_{pt} = \text{Data\_point} = \frac{\Delta T_1 + \Delta T_2 + \Delta T_3 + \dots + \Delta T_n}{n}$$

$$d\Delta T_{pt} = \left| \left( \frac{d}{d\Delta T_1} \Delta T_{pt} \right) \cdot \delta\Delta T_1 \right| + \left| \left( \frac{d}{d\Delta T_2} \Delta T_{pt} \right) \cdot \delta\Delta T_2 \right| + \dots + \left| \left( \frac{d}{d\Delta T_n} \Delta T_{pt} \right) \cdot \delta\Delta T_n \right|$$

$$\frac{d}{d\Delta T_1} \Delta T_{pt} = \frac{1}{n} \quad \dots \quad \frac{d}{d\Delta T_n} \Delta T_{pt} = \frac{1}{n}$$

$$d\Delta T_{pt} = \left| \frac{1}{n} \cdot \delta\Delta T_1 \right| + \left| \frac{1}{n} \cdot \delta\Delta T_2 \right| + \dots + \left| \frac{1}{n} \cdot \delta\Delta T_n \right| \quad \text{where } \delta\Delta T_n \text{ is given above as: } \delta\Delta T_n = 1.3 \text{ }^\circ\text{C}$$

$$d\Delta T_{pt} = \frac{1}{n} \cdot n \cdot \delta\Delta T_n = 1.3 \text{ }^\circ\text{C} \quad \text{So it doesn't matter how many data points are averaged, the uncertainty for a plotted point is constant at } \pm 1.3 \text{ }^\circ\text{C}.$$

Uncertainty calculations for  $Q_{in}$ :

$$\text{Power} = I^2 \cdot R = Q_{in} \quad R := 88.2 \cdot \text{ohm}$$

$$dQ_{in} = \left| \left( \frac{d}{dI} Q_{in} \right) \cdot \delta I \right| + \left| \left( \frac{d}{dR} Q_{in} \right) \cdot \delta R \right| = |2 \cdot I \cdot R \cdot \delta I| + |I^2 \cdot \delta R|$$

$$\frac{dQ_{in}}{Q_{in}} = \left| \frac{2 \cdot I \cdot R \cdot \delta I}{I^2 \cdot R} \right| + \left| \frac{I^2 \cdot \delta R}{I^2 \cdot R} \right| = \left| \frac{2 \cdot \delta I}{I} \right| + \left| \frac{\delta R}{R} \right|$$

The current is measured through a shunt resistor.

$$I = \frac{V}{R_{shunt}} \quad \delta I = \left| \left( \frac{d}{dV} I \right) \cdot \delta V \right| + \left| \left( \frac{d}{dR_{shunt}} I \right) \cdot \delta R_{shunt} \right| = \left| \frac{1}{R_{shunt}} \cdot \delta V \right| + \left| \frac{-V}{R_{shunt}^2} \cdot \delta R_{shunt} \right|$$

$$\frac{\delta I}{I} = \left| \frac{\frac{1}{R_{shunt}} \cdot \delta V}{\frac{V}{R_{shunt}}} \right| + \left| \frac{\frac{-V}{R_{shunt}^2} \cdot \delta R_{shunt}}{\frac{V}{R_{shunt}}} \right| = \left| \frac{\delta V}{V} \right| + \left| \frac{-\delta R_{shunt}}{R_{shunt}} \right|$$

$$R_{shunt} := 0.01 \cdot \text{ohm}$$

The shunt was known to be a precision resistor with 1% accuracy,  $\delta R_{shunt} := 1\% \cdot R_{shunt}$  thus:

$\delta V$  is found from the Fluke data acquisition system, the specifications for the millivolt range:  $0.01\% + 40 \cdot \mu\text{V}$

The maximum voltage that would be read at the shunt for the currents expected is 15 mV (which corresponds to 1.5 amps).

$$\mu\text{V} := 1 \cdot 10^{-6} \cdot \text{volt}$$

$$V := 1 \cdot \text{volt}$$

$$\delta V := 15 \cdot \text{mV} \cdot 0.01\% + 40 \cdot \mu\text{V}$$

$$15 \cdot \text{mV} \cdot 0.01\% = 0.0015 \cdot \text{mV}$$

$$\delta V = 0.0415 \cdot \text{mV}$$

$$40 \cdot \mu\text{V} = 0.04 \cdot \text{mV}$$

To be conservative  $\frac{\delta V}{V}$  will be estimated at the lowest expected voltage, that is for the 15 watt input.

At 15 watts the expected voltage is:  $I^2 \cdot R = 15 \cdot \text{watt}$  or  $I = \frac{1}{\sqrt{R}} \cdot \sqrt{15 \cdot \text{watt}}$

$$V_{\min} = I \cdot R_{\text{shunt}} \quad V_{\min} = 4.1239 \cdot \text{mV} \quad I = 0.4124 \cdot \text{amp}$$

$$\frac{\delta V}{V_{\min}} = 1.0063 \cdot \%$$

$$\frac{\delta I}{I} = \left| \frac{\delta V}{V_{\min}} \right| + \left| \frac{-\delta R_{\text{shunt}}}{R_{\text{shunt}}} \right| \quad \left| \frac{\delta V}{V_{\min}} \right| + \left| \frac{-\delta R_{\text{shunt}}}{R_{\text{shunt}}} \right| = 2.0063 \cdot \%$$

Now we can determine the uncertainty in  $Q_{\text{in}}$ :  $\frac{dQ_{\text{in}}}{Q_{\text{in}}} = \left| \frac{2 \cdot \delta I}{I} \right| + \left| \frac{\delta R}{R} \right| = 2 \cdot 2.0063 \cdot \% + 1 \cdot \%$

$$2 \cdot 2.0063 \cdot \% + 1 \cdot \% = 5.0126 \cdot \%$$

So the uncertainty in  $Q_{\text{in}}$  is:  $\frac{dQ_{\text{in}}}{Q_{\text{in}}} = 5.0126 \cdot \%$

Heat loss through insulation at evaporator:

Problem: Determine the heat loss from the loop heat pipe tests that flow through the

Assumptions: The flow will take place as a natural convection. The heat flow thru the insulation must balance that which is to the freestream by convection.

Solution: From Incropera and Dewitt's text on Heat transfer (1985, pages 391-401) we get the following Nusselt relations for free convection:

For horizontal surfaces:

$$\text{For upper surface of heated plate: } Nu_L = 0.54 \cdot Ra_L^{\frac{1}{4}} \quad 10^4 \leq Ra_L \leq 10^7$$

$$\text{For lower surface of heated plate: } Nu_L = 0.27 \cdot Ra_L^{\frac{1}{3}} \quad 10^5 \leq Ra_L \leq 10^{10}$$

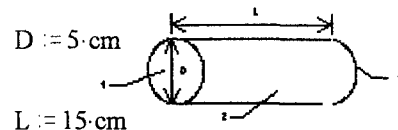
$$Ra_L = \frac{g \cdot \beta \cdot (T_s - T_{inf}) \cdot L^3}{\nu \cdot \alpha} \quad L = \frac{A_s}{P}$$

$$\text{For a long horizontal Cylinder: } Nu_D = \left[ 0.60 + \frac{0.387 \cdot Ra_D^{\frac{1}{6}}}{\left[ 1 + \left( \frac{0.559}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2 \quad 10^{-5} \leq Ra_L \leq 10^{12}$$

For vertical surfaces:

$$Nu_L = \left[ 0.825 + \frac{0.387 \cdot Ra_L^{\frac{1}{6}}}{\left[ 1 + \left( \frac{0.492}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2$$

The estimated dimensions of the cylinder used are:



To gain an appreciation for the magnitude of the effects of free convection on the heat loss through the insulation of the evaporator, two orientation will be evaluated; the evaporator vertical, the evaporator horizontal.

When the evaporator is vertical surfaces 1 and 3 will be considered horizontal surfaces (case 1). When the evaporator is horizontal surface 1 and 3 will be considered vertical surfaces and the sides considered as a cylinder (case 2).



Properties for air:

| T<br>(K) | $\nu$<br>$\left(\frac{\text{m}^2}{\text{sec}}\right)$ | $\alpha$<br>$\left(\frac{\text{m}^2}{\text{sec}}\right)$ | k<br>$\left(\frac{\text{watt}}{\text{m}\cdot\text{K}}\right)$ | Pr    |
|----------|---|--|---|-------|
| 250      | $11.44 \cdot 10^{-6}$                                 | $15.9 \cdot 10^{-6}$                                     | $22.3 \cdot 10^{-3}$  | 0.720 |
| 300      | $15.89 \cdot 10^{-6}$                                 | $22.5 \cdot 10^{-6}$                                     | $26.3 \cdot 10^{-3}$  | 0.707 |
| 350      | $20.92 \cdot 10^{-6}$                                 | $29.9 \cdot 10^{-6}$                                     | $30.0 \cdot 10^{-3}$  | 0.700 |

$$g := 9.81 \cdot \frac{\text{m}}{\text{sec}^2}$$

For all testing the ambient temperature was never below 22.2 C  $T_{\text{inf}} := (273.15 + 22.2) \cdot \text{K}$

The surface temperature at the outside of the insulation varies with the heat input to the evaporator but never exceeded 31.2 C:

$$T_s := (273.15 + 31.2) \cdot \text{K} \quad i := 0..2 \quad T_{\text{film}} := \frac{T_s + T_{\text{inf}}}{2} \quad \nu_{\text{values}_i} := \text{properties}_{i,1} \cdot \frac{\text{m}^2}{\text{sec}}$$

$$T_s - T_{\text{inf}} = 9 \cdot \text{K} \quad T_{\text{film}} = 299.85 \cdot \text{K} \quad T_{\text{values}_i} := \text{properties}_{i,0} \cdot \text{K}$$

$$\nu(T) := \text{linterp}(T_{\text{values}}, \nu_{\text{values}}, T) \quad \nu(T_{\text{film}}) = 1.588 \cdot 10^{-5} \cdot \frac{\text{m}^2}{\text{sec}} \quad \alpha_{\text{values}_i} := \text{properties}_{i,2} \cdot \frac{\text{m}^2}{\text{sec}}$$

$$\alpha(T) := \text{linterp}(T_{\text{values}}, \alpha_{\text{values}}, T) \quad \alpha(T_{\text{film}}) = 2.248 \cdot 10^{-5} \cdot \frac{\text{m}^2}{\text{sec}} \quad k_{\text{values}_i} := \text{properties}_{i,3} \cdot \frac{\text{watt}}{\text{m}\cdot\text{K}}$$

$$\beta(T) := \frac{1}{T} \quad \beta(T_{\text{film}}) = 0.003 \cdot \text{K}^{-1} \quad \text{Pr}_{\text{values}_i} := \text{properties}_{i,4}$$

$$k(T) := \text{linterp}(T_{\text{values}}, k_{\text{values}}, T) \quad k(T_{\text{film}}) = 0.026 \cdot \frac{\text{watt}}{\text{m}\cdot\text{K}}$$

$$\text{Pr}(T) := \text{linterp}(T_{\text{values}}, \text{Pr}_{\text{values}}, T) \quad \text{Pr}(T_{\text{film}}) = 0.707$$

For evaporator in vertical position:  $\text{Area}_{\text{sides}} := 2 \cdot \pi \cdot \frac{D}{2} \cdot L$   $\text{Area}_{\text{sides}} = 235.619 \cdot \text{cm}^2$

$$\text{Ra}_L(T_s, T_{\text{inf}}) := \frac{g \beta \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \left[ (T_s - T_{\text{inf}}) \cdot L^3 \right]}{\nu \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \alpha \left( \frac{T_s + T_{\text{inf}}}{2} \right)} \quad \text{Ra}_L(T_s, T_{\text{inf}}) = 2.784 \cdot 10^6$$

For vertical surfaces:

$$\text{Nu}_L(T_s, T_{\text{inf}}) := \left[ 0.825 + \frac{0.387 \cdot \text{Ra}_L(T_s, T_{\text{inf}})^{\frac{1}{6}}}{\left[ 1 + \left( \frac{0.492}{\text{Pr} \left( \frac{T_s + T_{\text{inf}}}{2} \right)} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2 \quad \text{Nu}_L(T_s, T_{\text{inf}}) = 21.825$$

$$\text{Nu} = \frac{h \cdot L}{k} \quad h(T_s, T_{\text{inf}}) = \frac{k \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \text{Nu}_L(T_s, T_{\text{inf}})}{L} \quad h(T_s, T_{\text{inf}}) = 3.825 \cdot \frac{\text{watt}}{\text{m}^2 \cdot \text{K}}$$

$$Q(T_s, T_{\text{inf}}) := \text{Area}_{\text{sides}} \cdot h(T_s, T_{\text{inf}}) \cdot (T_s - T_{\text{inf}})$$

$$Q(T_s, T_{\text{inf}}) = 0.811 \cdot \text{watt} \quad \text{This is the expected heat loss at the surface of the insulation for the sides only.}$$

For horizontal surfaces:

$$\text{Area}_{\text{ends}} := 2 \cdot \pi \cdot \left( \frac{D}{2} \right)^2$$

$$\text{For upper surface of heated plate: } \text{Nu}_L = 0.54 \cdot \text{Ra}_L^{\frac{1}{4}} \quad 10^4 \leq \text{Ra}_L \leq 10^7$$

$$\text{For lower surface of heated plate: } \text{Nu}_L = 0.27 \cdot \text{Ra}_L^{\frac{1}{3}} \quad 10^5 \leq \text{Ra}_L \leq 10^{10}$$

$$\text{Ra}_D(T_s, T_{\text{inf}}) := \frac{g \beta \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot [(T_s - T_{\text{inf}}) \cdot D^3]}{\nu \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \alpha \left( \frac{T_s + T_{\text{inf}}}{2} \right)} \quad \text{Ra}_D(T_s, T_{\text{inf}}) = 1.031 \cdot 10^5$$

$$\text{Nu}_{\text{Lupper}}(T_s, T_{\text{inf}}) := 0.54 \cdot \text{Ra}_D(T_s, T_{\text{inf}})^{\frac{1}{4}}$$

$$\text{Nu}_{\text{Lower}}(T_s, T_{\text{inf}}) := 0.27 \cdot \text{Ra}_D(T_s, T_{\text{inf}})^{\frac{1}{3}}$$

$$\text{Nu} = \frac{h \cdot L}{k} \quad h_{\text{up}}(T_s, T_{\text{inf}}) := \frac{k \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \text{Nu}_{\text{Lupper}}(T_s, T_{\text{inf}})}{D} \quad h_{\text{up}}(T_s, T_{\text{inf}}) = 5.088 \cdot \frac{\text{watt}}{\text{m}^2 \cdot \text{K}}$$

$$h_{\text{low}}(T_s, T_{\text{inf}}) := \frac{k \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \text{Nu}_{\text{Lower}}(T_s, T_{\text{inf}})}{D} \quad h_{\text{low}}(T_s, T_{\text{inf}}) = 6.657 \cdot \frac{\text{watt}}{\text{m}^2 \cdot \text{K}}$$

$$Q_v(T_s, T_{\text{inf}}) := \text{Area}_{\text{ends}} \cdot (h_{\text{up}}(T_s, T_{\text{inf}}) + h_{\text{low}}(T_s, T_{\text{inf}})) \cdot (T_s - T_{\text{inf}})$$

$$Q_v(T_s, T_{\text{inf}}) = 0.415 \cdot \text{watt} \quad \text{This is the expected heat loss from the ends only.}$$

Total heat loss of evaporator through the insulation:  $Q_v(T_s, T_{\text{inf}}) + Q(T_s, T_{\text{inf}}) = 1.226 \cdot \text{watt}$

Now for case 2, the evaporator horizontal:

$$\text{For a long horizontal Cylinder: } \text{Nu}_D(T_s, T_{\text{inf}}) := \left[ 0.60 + \frac{0.387 \cdot \text{Ra}_D(T_s, T_{\text{inf}})^{\frac{1}{6}}}{\left[ 1 + \left( \frac{0.559}{\text{Pr} \left( \frac{T_s + T_{\text{inf}}}{2} \right)} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2$$

for  $10^{-5} \leq \text{Ra}_L \leq 10^{12}$

For vertical surfaces:

(note  $\text{Ra}_D$  is used since for the horizontal configuration the ends will be the vertical surfaces)

$$\text{Nu}_L(T_s, T_{\text{inf}}) := \left[ 0.825 + \frac{0.387 \cdot \text{Ra}_D(T_s, T_{\text{inf}})^{\frac{1}{6}}}{\left[ 1 + \left( \frac{0.492}{\text{Pr} \left( \frac{T_s + T_{\text{inf}}}{2} \right)} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2$$

$$\text{Ra}_D(T_s, T_{\text{inf}}) = 1.031 \cdot 10^5$$

$$\text{Nu} = \frac{h \cdot L}{k} \quad h_{\text{sides}}(T_s, T_{\text{inf}}) := \frac{k \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \text{Nu}_D(T_s, T_{\text{inf}})}{D} \quad h_{\text{sides}}(T_s, T_{\text{inf}}) = 4.12 \cdot \frac{\text{watt}}{\text{m}^2 \cdot \text{K}}$$

$$h_{\text{ends}}(T_s, T_{\text{inf}}) := \frac{k \left( \frac{T_s + T_{\text{inf}}}{2} \right) \cdot \text{Nu}_L(T_s, T_{\text{inf}})}{D} \quad h_{\text{ends}}(T_s, T_{\text{inf}}) = 4.878 \cdot \frac{\text{watt}}{\text{m}^2 \cdot \text{K}}$$

$$Q_s(T_s, T_{inf}) := \text{Area}_{sides} \cdot h_{sides}(T_s, T_{inf}) \cdot (T_s - T_{inf}) \quad Q_s(T_s, T_{inf}) = 0.874 \cdot \text{watt}$$

$$Q_e(T_s, T_{inf}) := \text{Area}_{ends} \cdot h_{ends}(T_s, T_{inf}) \cdot (T_s - T_{inf}) \quad Q_e(T_s, T_{inf}) = 0.172 \cdot \text{watt}$$

$$\text{Total heat loss for the horizontal configuration } Q_s(T_s, T_{inf}) + Q_e(T_s, T_{inf}) = 1.046 \cdot \text{watt}$$

So we see that the vertical configuration is the worst case configuration and it has less than a 1.23 watt heat loss at the evaporator. This then provides good confidence that the majority of the heat input to the evaporator does indeed enter the evaporator.

At a heat input of 75watts, 1.23 watts is 1.6% of the heat loss

### Uncertainty calculations for $Q_{out}$ :

Determining the error for the heat out at the condenser end.

$$Q_{out}(V_{dot}, c_p, \rho, \Delta T) := V_{dot} \cdot \rho \cdot c_p \cdot \Delta T \quad m_{dot} = V_{dot} \cdot \rho$$

$$dQ_{out}(V_{dot}, c_p, \rho, \Delta T, \delta V_{dot}, \delta c_p, \delta \rho, \delta \Delta T) := \left| \left( \frac{d}{dV_{dot}} V_{dot} \cdot \rho \cdot c_p \cdot \Delta T \right) \cdot \delta V_{dot} \right| \dots$$

$$+ \left| \left( \frac{d}{d\rho} V_{dot} \cdot \rho \cdot c_p \cdot \Delta T \right) \cdot \delta \rho \right| \dots$$

$$+ \left| \left( \frac{d}{dc_p} V_{dot} \cdot \rho \cdot c_p \cdot \Delta T \right) \cdot \delta c_p \right| \dots$$

$$+ \left| \left( \frac{d}{d\Delta T} V_{dot} \cdot \rho \cdot c_p \cdot \Delta T \right) \cdot \delta \Delta T \right|$$

$$V_{dot} := 0.15 \cdot \frac{\text{liter}}{\text{min}} \quad \rho := .99823 \cdot 10^3 \cdot \frac{\text{kg}}{\text{m}^3} \quad c_p := 4.1819 \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

The flow rate was maintained between 0.1 liters/min and 0.2 liter/min for the majority of testing. For some tests it was higher, but typically did not exceed 0.4 liter/min.

$$\Delta T := 1.5 \cdot \text{K}$$

It was attempted to maintain the difference in temperature to at least 2 °C. For some of the low  $Q_{in}$  values this dropped to 1.5 °C.

For the flowmeter the specifications indicated an accuracy of 1% of the flow:

$$\delta V_{dot} := 1\% \cdot V_{dot}$$

The change in density and specific heat are estimated at 1%

$$\delta \rho := 1\% \cdot \rho \quad \delta c_p := 1\% \cdot c_p$$

From the Fluke the uncertainty in the temperature measurements is 1.3 C for a difference between temperatures

$$\delta \Delta T := 1.3 \cdot \text{K}$$

$$dQ_{out}(V_{dot}, c_p, \rho, \Delta T, \delta V_{dot}, \delta c_p, \delta \rho, \delta \Delta T) = 14.037 \cdot \text{watt} \quad V_{dot} \cdot \rho \cdot c_p \cdot \Delta T = 15.654 \cdot \text{watt}$$

As a percentage the uncertainty is calculated as:

$$dQ_{\text{out}}\%(\dot{V}, c_p, \rho, \Delta T, \delta \dot{V}, \delta c_p, \delta \rho, \delta \Delta T) := \frac{dQ_{\text{out}}(\dot{V}, c_p, \rho, \Delta T, \delta \dot{V}, \delta c_p, \delta \rho, \delta \Delta T)}{Q_{\text{out}}(\dot{V}, c_p, \rho, \Delta T)}$$

For the given values above, which represent a conservative estimate the uncertainty as percentage is found to be:

$$dQ_{\text{out}}\%(\dot{V}, c_p, \rho, \Delta T, \delta \dot{V}, \delta c_p, \delta \rho, \delta \Delta T) = 89.7\%$$

**Appendix D: Test Matrix**

| Test # | $\Delta H$<br>(meters) | Coolant<br>Temperature<br>(°C) | Evaporator<br>Angle<br>(degrees) | Condenser<br>Angle<br>(degrees) |
|--------|------------------------|--------------------------------|----------------------------------|---------------------------------|
| 3      | 0                      | 20                             | 0                                | 0                               |
| 4      | 0                      | 20                             | 45                               | 0                               |
| 5      | 0                      | 20                             | 135                              | 0                               |
| 6      | 0                      | 20                             | 90                               | 0                               |
| 7      | 0                      | 20                             | 0                                | 45                              |
| 8      | 0                      | 20                             | 0                                | 90                              |
| 9      | 0                      | 20                             | 0                                | -45                             |
| 10     | 0                      | 20                             | 0                                | -90                             |
| 11     | 0                      | 40                             | 0                                | -90                             |
| 12     | 0                      | 40                             | 0                                | 0                               |
| 13     | 0                      | 40                             | 45                               | 0                               |
| 14     | 0                      | 40                             | 90                               | 0                               |
| 15     | 0                      | 40                             | 135                              | 0                               |
| 16     | 0                      | 40                             | -45                              | 0                               |
| 17     | 0                      | 40                             | -90                              | 0                               |
| 18     | 0                      | 40                             | 0                                | 45                              |
| 19     | 0                      | 40                             | 0                                | 90                              |
| 20     | 0                      | 40                             | 0                                | -45                             |
| 21     | 0                      | 20                             | -45                              | 0                               |
| 22     | 0                      | 20                             | -90                              | 0                               |
| 23     | 0.61                   | 20                             | 0                                | 0                               |
| 24     | 1.22                   | 20                             | 0                                | 0                               |
| 25     | 1.83                   | 20                             | 0                                | 0                               |
| 26     | 2.44                   | 20                             | 0                                | 0                               |
| 27     | 2.79                   | 20                             | 0                                | 0                               |
| 28     | 0.61                   | 20                             | 0                                | 0                               |
| 29     | 1.22                   | 20                             | 0                                | 0                               |
| 30     | 1.83                   | 20                             | 0                                | 0                               |

| Test # | $\Delta H$<br>(meters) | Coolant<br>Temperature<br>(°C) | Evaporator<br>Angle<br>(degrees) | Condenser<br>Angle<br>(degrees) |
|--------|------------------------|--------------------------------|----------------------------------|---------------------------------|
| 31     | 2.44                   | 20                             | 0                                | 0                               |
| 32     | 2.79                   | 20                             | 0                                | 0                               |
| 33     | 2.44                   | 20                             | 45                               | 0                               |
| 34     | 2.44                   | 20                             | 90                               | 0                               |
| 35     | 2.44                   | 20                             | -45                              | 0                               |
| 36     | 2.44                   | 20                             | -90                              | 0                               |
| 37     | 2.44                   | 20                             | 0                                | 45                              |
| 38     | 2.44                   | 20                             | 0                                | 90                              |
| 39     | 2.44                   | 20                             | 0                                | -45                             |
| 40     | 2.44                   | 20                             | 0                                | -90                             |
| 41     | 1.22                   | 20                             | 0                                | -90                             |
| 42     | 1.22                   | 20                             | 0                                | -45                             |
| 43     | 1.22                   | 20                             | 0                                | 45                              |
| 44     | 1.22                   | 20                             | 0                                | 90                              |
| 45     | 1.22                   | 20                             | 45                               | 0                               |
| 46     | 1.22                   | 20                             | 90                               | 0                               |
| 47     | 1.22                   | 20                             | -45                              | 0                               |
| 48     | 1.22                   | 20                             | -90                              | 0                               |



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## Vita

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| <b>13. ABSTRACT (Maximum 200 words)</b><br>This research examined the effects on performance of varying angular orientation and height differences between evaporator and condenser for a loop heat pipe. Performance was defined as the difference in temperature between evaporator and condenser ( $\Delta T$ ). The pipe was evaluated at varying input power ( $Q_{in}$ ) for: varying evaporator and condenser angles, different coolant temperatures, and varying relative height differences. All analysis included only steady state operation. The performance was influenced by condenser angles, with an optimal condenser angle for best performance being +45 degrees from horizontal. Additionally, the evaporator angles were found to influence performance only at low $Q_{in}$ and low coolant temperatures. For high $Q_{in}$ , performance was independent of evaporator angle. For small $Q_{in}$ the $\Delta T$ increased (poorer performance) with decreasing coolant temperature. However, for high $Q_{in}$ the $\Delta T$ was independent of coolant temperature. For small $Q_{in}$ , the $\Delta T$ increased with increasing heights of evaporator over condenser. However, for high $Q_{in}$ the $\Delta T$ was independent of the height difference. Additionally, pipe operation was sensitive to the rate of decrease of $Q_{in}$ . Finally, an unexplained anomaly shows the pipe to operate at two different $\Delta T$ values for a given heat input. |   |  |   |  |
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