Fabrication, Testing and Analysis of Heat Pipes for Heat Recovery

A Project Report

Submitted by

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ABSTRACT

Energy is an important input for development. The need for energy is increasing day by day. The present energy situations are characterized by high rate of growth of energy consumption and increasing dependence on finite sources of energy. To break away from the past trends that are not sustainable and to build on a future of hope and strength, the most reliable strategy is "Energy Saving and Conservation".

The need for maximization of heat recovery requires better technology than the present one. The convection mode of heat transfer will be effective than the conduction mode of heat transfer. Heat pipes works on the principle of convection. Heat is given as input to the condenser end and is rejected at the evaporator end with minimal losses. The middle region called adiabatic region has no change in temperature throughout the length. When the evaporator end is connected to the waste heat source and the condenser unit is linked to the heat recovering medium, heat is recovered with minimum losses. Hence this could be more preferable method for heat recovery than the solid type heat exchangers.

Our project "Fabrication, testing and analysis of heat pipe for heat recovery" aims at fabricating a copper water heat pipe of three different lengths. The three heat pipes are tested for various heat transfer limitations. Characteristics curves are drawn for the three pipes. From the analysis the most suitable one for heat recovery is selected. It is then used for recovering heat energy from the exhaust of an I.C. engine. Water is used as heat recovering medium, which is passed through the condenser end of the heat exchanger and hot water is obtained. A correlation is developed for heat pipe heat recovery in terms of load and mass flow rate. The developed correlation is helpful in analyzing the performance of the heat pipe heat exchanger. Optimization is done using SYSTAT software and the optimum operating parameters are obtained.

Keywords: Convection, Evaporator, Condenser, HPHE-Heat Pipe Heat Exchanger.

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CHAPTER 1

INTRODUCTION

1.1 CURRENT TREND

The huge demand in energy of this revolutionary world calls for various new sources of energy as the existing fossils are depleting. Hence various ways for new sources are been analysed day to day. But instead of new ones, converting the waste into useful could act as another source. This is called recovery from waste. The energy emitted into the atmosphere can be converted into useful by recovering called waste heat recovery. At present there are various systems that could serve for waste heat recovery. Commercially available systems are based on the mode of conduction. But due to the losses in this system, it requires for higher technology that recovers more heat from the heat rejecting systems. As convection is more efficient than conduction, it is possible to recover more heat with the help of fluids instead of solids. Since radiation requires no medium for heat transfer only convection could be the better possible mode than conduction. Hence the present trend is going for heat recovery through convection heat transfer.

1.2 PROJECT IMPORTANCE

The heat pipe is one such equipment which is used in thermal applications. They can transfer heat from one point to the other with least loss which helps in increasing the heat transfer efficiency. Once the waste heat is transferred, the waste heat can be used for other process which is secondary in nature. Though the processes are secondary in nature they show a notable increase in the efficiency of the overall system by using waste heat instead of fresh energy. Thus the application of heat pipes is to recover the waste heat and use it for improving the efficiency of the system

1.3 SCOPE OF THE PROJECT

We arrived at a solution of heat pipe heat exchanger to recover the waste heat more efficiently than the available conventional type heat exchanger. This heat pipe is made up of copper pipes with fins at the end of the condenser. Copper wick of mesh no.160 is used inside the pipe. The fluid for conduction is used as distilled water. Though there are a number of heat pipes available for cooling purpose, our aim is to recover the heat from waste heat sources. Hence the conduction mode of heat transfer could be better than the conduction mode.

Cheaper metals like aluminium, stainless steel and others could be used instead of copper. At present heat pipes are available for cooling applications only. For example, cooling of chips in computers using miniature heat pipes, cooling of aircraft fins with the help of leading edge heat pipes. So in near future heat pipe will have wide scope for heat recovery. Heat pipe heat exchanger will be a better unit to recover the waste heat. We can vary the heat transfer rate of the heat pipe by varying the working fluids, so that they can be used for various operating temperatures. Similarly the length and cross section of the heat pipe can be varied for increasing the heat recovery rate. Wick structures play important role in the capillary action of the heat pipe. Therefore increasing the number of layers of wick structure, we can vary the capillary action. Recently popular and most used wick structure is the sintered wick structure.

1.4 SEQUENCE OF PROJECT

1. First we studied the basic and the principles of heat pipes. Knowledge of different types of heat pipe will be useful to select the suitable one for heat recovery.
2. We have selected three heat pipes of different length and fabricated to the required dimension. They are then tested under standard conditions. The results are then analysed and the better pipe is selected for heat recovery process.
3. The selected pipe is redesigned with a heat exchanger unit and then tested in the exhaust line of the I.C engine by passing a known quantity of water into the heat exchanger which will recover the heat from it. Then the recovered heat is calculated.

1.5 LIMITATIONS IN PROJECT

Heat pipes have their own limitations. They have limits within which they operate efficiently than other temperature called operating temperature. When they are heated beyond a limit, burnout of hear pipes occurs. (ie,) the wall of the heat pipes gets over heated due to lack of liquid . As a result the walls get damaged and therefore the life of the heat pipe gets reduced drastically. Hence the heat pipes must be operated within the particular range. Similarly the fluid inside the pipe also plays important factor for determining the working of heat pipe. If excess fluid is present in the pipe then there will always be a portion of liquid in the evaporator section. Like wise for heat recovery bundle of heat pipes are necessary to extract more heat from the waste heat sources.

CHAPTER 2

HEAT PIPES

2.1 INTRODUCTION

The introduction of the heat pipe was first conceived by Gaugler (1944) of the general motors corporation in the U.S. Patent No.2350348. Gaugler, who was working on refrigeration problems at that time, envisioned a device which would evaporate a liquid at a point above the place where condensation would occur without requiring any additional work to move the liquid to the higher elevation. His device consisted of a closed tube in which the liquid would absorb heat one location causing the liquid to evaporate. The vapor would then travel down the length of the tube where it would recondense and release its latent heat. It would then travel back up to a higher point; Gaugler suggested the use of a capillary structure consisting of sintered iron wick. A refrigeration unit proposed by Gaugler used a heat pipe to transfer the heat from the interior of a compartment to a pan of crushed ice below. However, his idea was not used by general motors for the refrigeration problem.

2.2 HEAT PIPE BASICS

A heat pipe is a device that efficiently transports heat from its one end to the other. It utilizes the latent heat of the vaporized working fluid instead of the sensible heat. As a result, the effective thermal conductivity may be several orders of magnitudes higher than that of the good solid conductors. Figure1 shows a schematic of a heat pipe operation. Heat input at the evaporator vaporizes the working fluid and this vapor travels to the condenser section. Here the latent heat is rejected via condensation. The vapor of the working fluid condenses and the condensate returns to the evaporator by means of capillary action. A heat pipe consists of a sealed container, a wick structure, a small amount of working fluid that is just sufficient to saturate the wick and it is in equilibrium with its own vapor.

The operating pressure inside the heat pipe is the vapor pressure of its working fluid. The length of the heat pipe can be divided into 3 parts viz. evaporator section, adiabatic section and condenser section. In a standard heat pipe, the inside of the container is lined with a wicking material. Space for the vapor travel is provided inside the container. Fins may be attached to the evaporator and the condenser portion to increase heat transfer rate depending upon the application.

2.3 TYPES OF HEAT PLIPES

- TWO-PHASE CLOSED THERMOSYPHON
- CAPILLARY-DRIVEN HEAT PIPE
- ANNULAR HEAT PIPE
- FLAT-PLATE HEAT PIPE
- ROTATING HEAT PIPE
- LEADING EDGE HEAT PIPE
- GAS-LOADED HEAT PIPE
- CAPILLARY PUMPED LOOP HEAT PIPE
- MONOGROOVE HEAT PIPE

2.4 OPERATING PRINCIPLE OF CAPILLARY DRIVEN HEAT PIPE

A heat pipe operates on a closed two phase cycle. Fig 2.1.shows a schematic of a typical heat pipe operation. As previously mentioned, there is liquid-vapor equilibrium inside the heat pipe. When the heat is supplied to the evaporator, this equilibrium breaks down as the working fluid evaporates. The generated vapor is at a higher pressure than the liquid and it travels to the condenser section through the vapor space provided. Vapor condenses giving away its latent heat of vaporization to the heat sink. The capillary pressure created in the menisci of the wick pumps the condensed fluid back to the evaporator section. The cycle repeats and the heat is continuously transported from evaporator to condenser in the form of latent heat of vaporization.

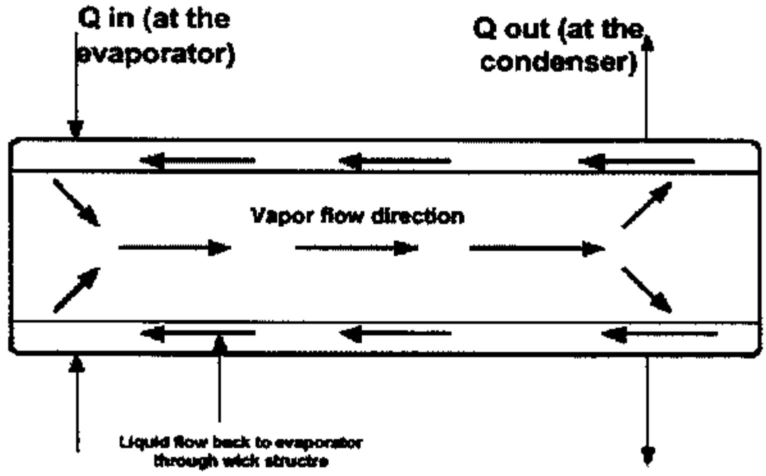

FIG 2.1 SCHEMATIC OF A TYPICAL HEAT PIPE

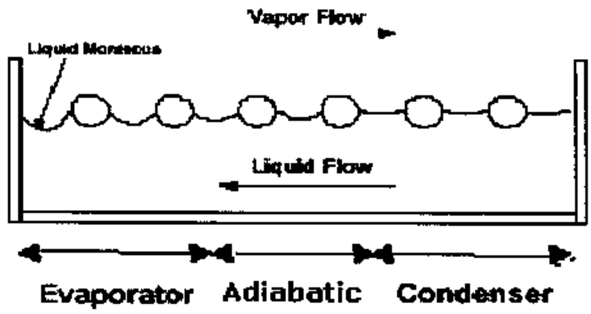

FIG. 2.2 VARIATION OF MENISCUS CURVATURE AS A FUNCTION OF AXIAL POSITION

When heat is applied to the evaporator, the liquid recedes into the pores of the wick and thus the menisci at the liquid-vapor interface are highly curved. This phenomenon is shown in Fig.2.2. At the condenser end, the menisci at the liquid-vapor interface are nearly flat during the condensation. The difference in the curvature of menisci driving force that circulates the fluid against the liquid and vapor pressure losses and body forces such as gravity (if there is an adverse tilt with respect to the ground).

2.5 HEAT PIPE THEORY

There are different heat transfer limits that govern the performance of a heat pipe. These will be discussed in brief in this section.

2.5.1 THE WORKING FLUID

Every heat pipe application has a particular temperature range in which the heat Pipe needs to operate. As a rule of thumb, the useful range extends from the point where the saturation pressure is greater than 0.1 atm and less than 20 atm. below 0.1 atm, the vapor pressure limit may be approached while above 20atm, the container thickness must be increased to a point where the heat pipe operation is limited by the increased thermal resistance.

2.5.2 THE WICK

The wick structure in a heat pipe facilitates liquid return to the evaporator from the condenser. The main purposes of the wick are to generate the capillary pressure, and to distribute the liquid around the evaporator section of heat pipe. Fig.2.3 shows various wick structures. The most commonly used wick structure is a wrapped screen wick. At this point, we will define a parameter called 'Mesh Number' which is used to specify a particular wrapped screen wick. It is defined as the number of wires per linear inch, counted from the center of any wire to a point exactly one inch distant, including the fractional distance between wires thereof. For example a mesh number of 60 per inch can be interpreted as 60×60 mesh wires per inch. A mesh could be square or rectangular mesh. Obviously, higher mesh number represents a finer grid.

The important requirements of a wick structure are listed below:

- Should be compatible with the wick and container material
- High latent heat
- High thermal conductivity
- High surface tension
- Low liquid and vapor viscosities
- Wettability of wick and wall materials

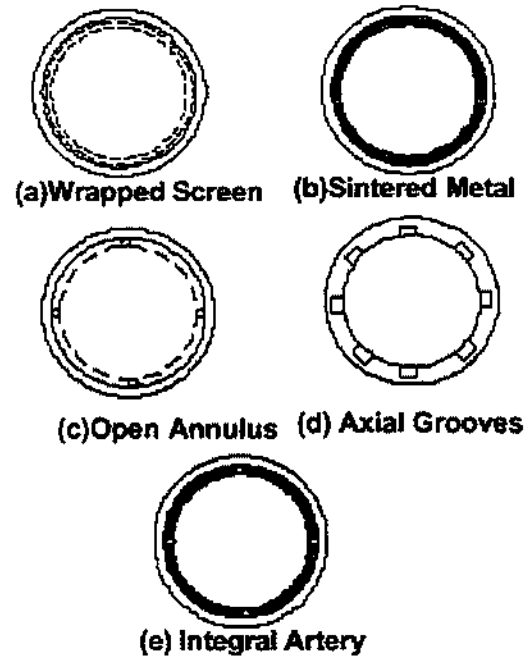

FIG.2.3 VARIOUS WICK STRUCTURES

2.5.3 CAPILLARY LIMIT

Ability of a capillary structure to provide the circulation for a given working fluid is called capillary limit or hydrodynamic limit. It occurs when the pumping rate is not sufficient to provide enough liquid to the evaporator section. To understand this heat transfer limit, it is essential to know the capillary action and the phenomenon that governs it.

Surface Tension:

There exists a small region surrounding the meniscus, where the density of both liquid and vapor vary gradually. In this region, close range repulsive forces decrease more significantly than longer range attractive forces. Normal to the interface this pressure imbalance tends to draw the vapor molecules toward the liquid surface. It is this interfacial tension resulting from stored energy of the molecules which is called 'surface tension'. It is seen from Fig. 2.4 that the cohesive forces between molecules down into a liquid are shared with all neighboring atoms. Those on the surface have no neighboring atoms above and exhibit stronger attractive forces upon their nearest neighbors on the surface. The effect of this is the formation of surface "film" which makes it more difficult to move an object through the surface than to move it when it is completely submersed.

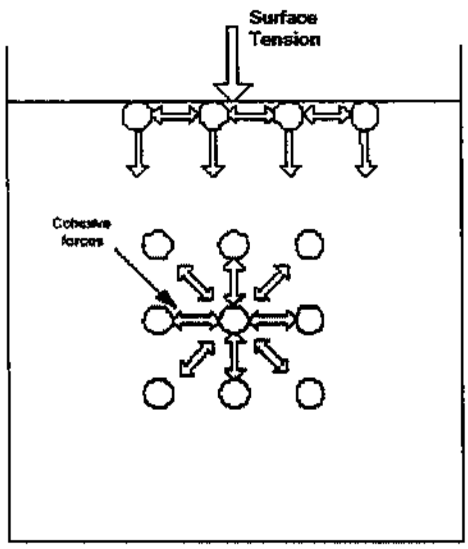

FIG2.4 MOLECULAR FORCES AND SURFACE TENSION

Cohesion:

When intermolecular attractive forces are between like molecules, they are referred to as cohesive forces. For example, the molecules of a water droplet are held together by cohesive forces, and the especially strong cohesive forces at the surface constitute surface tension.

Adhesion:

When the attractive forces are between unlike molecules, they are said to be adhesive forces. The adhesive forces between water molecules and the walls of a glass tube are stronger than the cohesive forces lead to an upward turning meniscus at the walls of the vessel and contribute to capillary action.

Capillary action is the result of adhesion and surface tension. Adhesion of wetting fluid to the walls of a vessel will cause an upward force on the liquid at the edges and result in a meniscus which turns upward. The surface tension acts to hold the surface intact, so instead of just the edges moving upward, the whole liquid surface is dragged upward.

2.5.4 CAPILLARY PRESSURE BALANCE

Let us first know the definition of two important terms. They are:

Dry point:

At this point the meniscus has minimum radius of curvature. It usually occurs in the evaporator at a point furthest from condenser.

Wet point:

The meniscus has maximum radius of curvature and thus the vapor and liquid pressure is approximately equal. This point typically occurs near the end of condenser farthest from the evaporator.

The relative positions of dry and wet points are shown in Fig. 2.5. This figure represents a simplified representation of pressure variation within a heat pipe. A more detailed explanation of the pressure variation will be given in the following section.

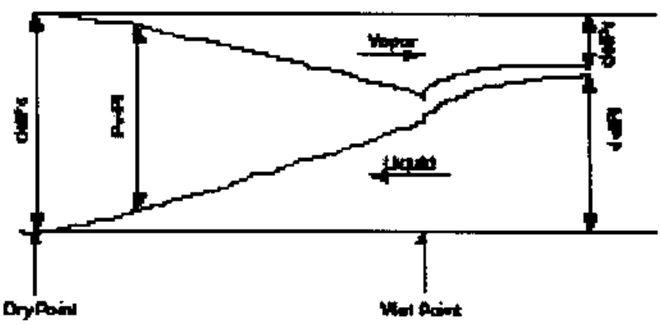

FIG 2.5 PRESSURE VARIATION & RELATIVE POSITIONS OF DRY AND WET POINTS FOR A HEAT PIPE

For proper operation of a heat pipe, the net capillary pressure difference between dry and wet points must be greater than the summation of all the pressure losses occurring throughout the liquid and vapor flow paths. This is called the capillary limitation.

2.5.5 TEMPERATURE-ENTROPY DIAGRAM

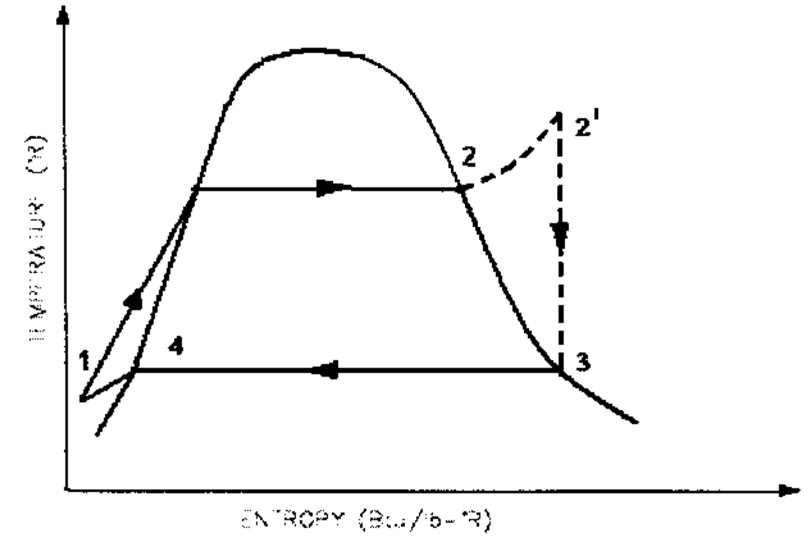

FIG 2.6 TEMPERATURE-ENTROPY DIAGRAM OF HEAT PIPE.

The temperature-Entropy diagram (Fig. 2.6) is helpful in understanding the phase change of the working fluid. At the point 1 the fluid is in liquid state. When it absorbs heat from the evaporator section, the sensible heat increases the temperature of the liquid till saturation curve. Then the temperature becomes constant and the available heat is the latent heat. Now the phase gradually changes from liquid to vapor and after it reaches the vapor state, it becomes super heated state. After it reaches the condenser end it losses its latent heat fro 2 to 3. When it reaches the point 3 it is liquid but still at high temperature. When it comes from 3 to 4 it looses its sensible heat completely and finally becomes low temperature at 4.

2.5.6 SONIC LIMIT

The evaporator condenser sections of a heat pipe represent a vapor flow channel with mass addition and extraction due to the evaporation and condensation respectively. The vapor velocity increases along the evaporator and reaches a maximum at the end of the evaporator section. The limitation of such a flow system is similar to that of a converging-diverging nozzle with a constant mass flow rate, where the evaporator exit corresponds to the throat of the nozzle.

Therefore, one expects that the vapor velocity at that point exceed the local speed of the sound. This chocked flow condition is called sonic limitation. The sonic limit usually occurs during the heat pipe startup or during the steady state operation when the heat transfer co-efficient at the condenser is high. The sonic limit is usually associated with liquid–metal heat pipes due to high vapor velocities and low densities. When the sonic limit is exceeded, it does not represent a serious failure, as does the capillary limit. The sonic limitations corresponds to a given evaporator end cap temperature. Increasing the evaporator end cap of heat transfer will not increase by decrease in the condenser temperature under the chocked condition. Therefore, when the sonic limit is reached, further increases in the heat transfer rate can be realized only when the evaporator temperature increases. Operation of heat pipes with heat rate close to or at the sonic limit results in a significant axial temperature drop along the heat pipe.

2.5.7 BOILING LIMIT

If the radial heat flux in the evaporator section becomes too high, the liquid in the evaporator wick boils and the wall temperature becomes excessively high. The vapor bubbles tat form in the wick prevents the liquid from wetting the pipe wall, which causes hot spots. If this boiling is severe it dries out the wick in the evaporator, which is defined as the boiling limit. However, under a low or moderate radial heat flux, low intensity stable boiling is possible with out boiling dry out. It should be noted that the boiling limitation is a radial heat flux limitation as compare to an axial eat flux limitation for the other heat pipe limits. However, since they are related through the evaporator surface area, the maximum radial heat flux limitations also specify the maximum axial heat transport. The boiling limit is often associated with heat pipes of non-metallic working fluids. For liquid-metal heat pipe, the boiling limit is rarely seen.

2.5.8 ENTRAINMENT LIMIT

A shear force exists at the liquid-interface since the vapor and liquid move in opposite directions. At high relative velocities, droplets of liquids can be torn from the wick surface and entrained into the vapor flowing towards the condenser section. If the entrainment becomes too great, the evaporator will dry out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe. The entrainment limit is often associated with low or moderate temperature heat pipes with smaller diameter, or higher temperature heat pipes when the heat input at the evaporator is high.

2.5.9 VAPOUR PRESSURE LIMIT

At low operating temperatures, viscous forces may be dominant for the vapor flow down the heat pipe. For a long liquid –metal heat pipe, the vapor pressure at the condenser end may be reducing to zero. The heat transport of the heat pipe may be limited under this condition. The vapor pressure limit is encountered when a heat pipe operates at temperatures below its normal operating range, such as during startup from the frozen state. In this case, the vapor pressure is very small, with the condenser end cap pressure nearly zero.

2.5.10 PRESSURE LOSS AND NET INCREASE IN AIR DENSITY

Robinson and Briggs correlations (Kuppan, 2000) are used for the pressure loss calculations. These correlations are based on the isosceles triangular layout for the high finned tubes. Based on this, the friction factor '*f*' is defined as follows:

$$f = 9.465 * Re_d^{-0.316} (S*T/D) (S*T/S*L)$$

Where,

f = Friction number

Re_d = Reynolds number

ST= Transverse tube pitch

SL= Longitudinal tube pitch

D=Tube diameter

The density of air increases with the decrease in its temperature but this increase is affected by the pressure loss associated with the implementation of heat exchanger in the inlet air duct. This can be illustrated by the following ideal gas equation.

Ideal gas equation can be written as,

$$\mathbf{PV = mRT}$$

Mass m can be written as,

$m = \rho V$

$\rho_{out} = (P_{atm} - \Delta P)/(R*T)$

$P*V = (\rho*V*R*T) \Rightarrow \rho = (P/R*T)$

% increase in $\rho = 100*\{(\rho_{out} - \rho_{in})/\rho_{in}\}$

Where,

ρ_{in} , ρ_{out} = Air density before and after cooling respectively

P_{atm} = Atmospheric pressure

$P\ \Delta$ = Pressure drop across heat exchanger

R =Universal gas constant

T = Temperature of the air

V=Volume of the air

For a finned tube heat exchanger, the results obtained after the simulation are listed below:

- Surface temperature at which heat pipe evaporator is to be maintained of 57°F
- 1.22 in heat pipe outer diameter
- 72 heat pipes with 8 tubes in the transverse and 9 in the longitudinal direction
- 90 fins per tube that create a fin density of 55 per linear ft (180 per linear meter);
- An air density of 1.178 kg / m $_3$ after HPHE
- An air temperature of 69°F after HPHE
- 3.75% net increase in air density.

2.6 HEAT PIPE CHARACTERISTICS HIGH EFFECTIVE THERMAL CONDUCTIVITY

The heat pipe is a device of very high thermal conductance. For examples, a temperature difference of 900°C is needed to transfer 1KW heat across a 30-mm-diameter 1-m-long copper rod. A heat pipe of the same size can transfer the same amount of heat with a temperature of less than 10°C. The Fig. 2.7 and Fig. 2.8 indicates that the heat pipe can have a thermal conductivity 90 times higher than that of a copper bar of the same size. Numerous heat pipe designs have been developed for various applications with varied heat transport capabilities.

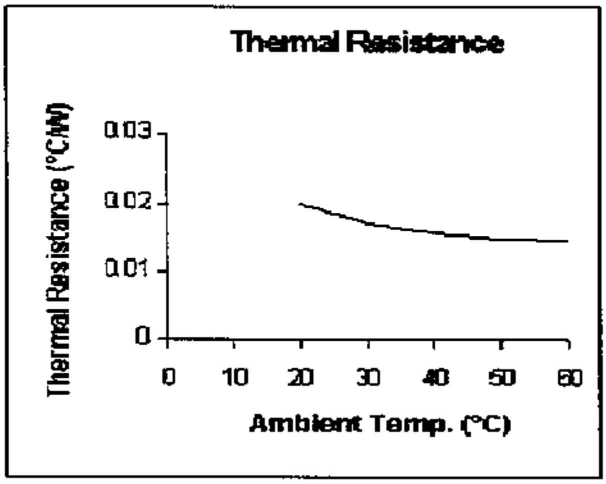

FIG 2.7 THE TEMPERATURE RESISTANCE OF HEAT PIPE VS. AMBIENT TEMPERATURE.

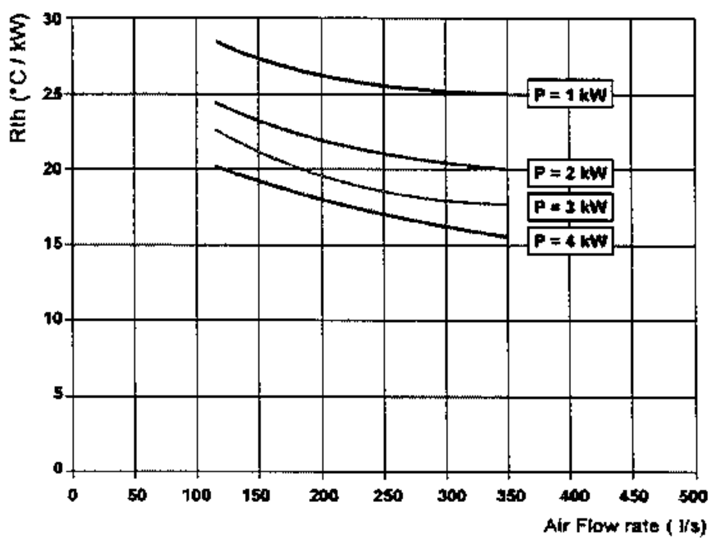

FIG.2.8 THE TEMPERATURE RESISTANCE OF HEAT PIPE VS AIR FLOW RATE

2.7 WORKING WITH EXTRUSIONS

Correction Factors

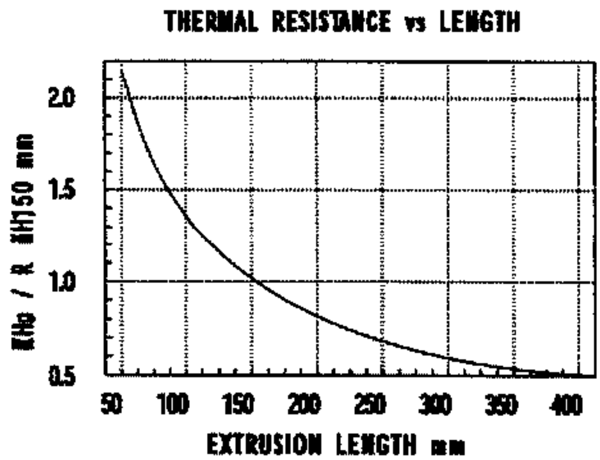

FIGURE 2.9 TEMPERATURE RESISTANCE VS.LENGTH

Because the air heats up while circulating through the extrusion, the convection coefficient is not constant throughout the extrusion length. Therefore, the thermal resistance changes nonlinearly as the length changes. To calculate the correct thermal resistance for extrusion lengths other than the standard 150 mm length, multiply the given thermal resistance data by the appropriate factor taken from the Thermal Resistance vs. Length graph shown in Fig. 2.9. The same correction factor must be used for thermal resistance in both natural convection and forced convection.

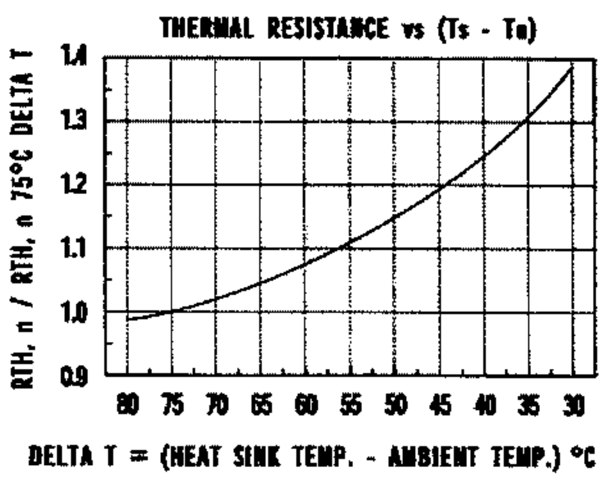

FIGURE 2.10 THERMAL RESISTANCE VS. (TS-TA)

Both natural convection and radiation coefficients are related to the sink-to-ambient temperature difference. To evaluate the thermal performance of a heat sink for an application requiring a sink-to-ambient temperature rise other than 75°C, use the correction factor from the Thermal Resistance vs (Ts - Ta) graph shown in Fig. 2.10. This factor must be used only for thermal resistance in natural convection.

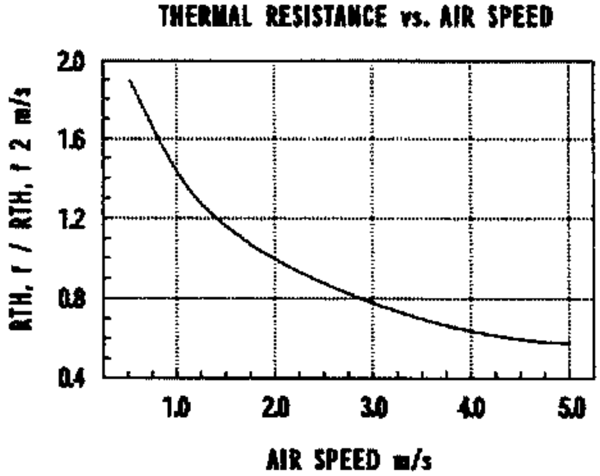

FIGURE 2.11 THERMAL RESISTANCE VS. AIR SPEED

The convection coefficient is also closely related to the air speed through the fins. Since evaluation of air speed through fins is difficult to evaluate under normal circumstances, we show the thermal resistance of an extrusion in forced convection evaluated using a tunnel the same size as the extrusion. For tunnel airflow other than 2 m/s, refer to the factor in the Thermal Resistance vs. Air Speed graph shown in Fig. 2.11. Use this factor to figure thermal resistance in forced convection.

2.8 HEAT PIPE APPLICATIONS

Heat pipes have been applied in many ways since their introduction in1964. Depending on their intended use, heat pipes can operate over a temperature range from 4.0 to 3000K. In all cases, their applications can be divided into three main categories: separation of heat source and sink, temperature equalization, and temperature control. Due to their extremely high thermal conductivity, heat pipes can efficiently transport heat from a concentrated source to a remotely mounted sink. This property can enable dense packing of electronics, for example, without undue regard for heat sink space requirements. Another benefits of the high thermal conductivity if the ability to provide an accurate method of temperature equalization. For example, a heat pipe mounted between two opposing faces of an orbiting platform will enable both faces to maintain constant and equal temperatures, thus minimizing thermal stresses. The temperature control is a result of the capability of heat pipes to transport large quantities of heat very rapidly. This feature enables a source of varying flux to be kept at a constant temperature as long as the heat flux extremes are within the operating range of the heat pipe.

CHAPTER 3

WASTE HEAT RECOVERY

3.1 WASTE HEAT RECOVERY-DEFINITION

The method of extracting heat from the process in which useless heat is rejected from one system to another system is called heat recovery. Heat recovery is a energy saving process in which cost of a industrial unit or any other system that uses this technique is reduced. This recovered heat is used back by the same system or different system.

3.2 APPLICATIONS

WASTE HEAT RECOVERY AND SPACE HEATING

HPHE applications are used in the process waste heat recovery for space heating. In this application, the temperatures encountered by the HPHE are significantly higher than in HVAC applications. Further more, the temperature difference between the two fluid streams is much larger. For instance the low temperature stream is normally ambient air as compared to process exhaust gas, which can be as high as 200C. In these applications the presence of pollutants in the high temperature streams must be accounted for by increasing the fin spacing on the evaporator side of the HPHE to approximately 20mm. however, since the desired purpose of this unit is to preheat air for space heating, the HPHE efficiency can be less than optimal. Heat pipe elements for HPHE are used in exhaust waste heat recovery for space heating is typically constructed of copper for lower temperature exhaust streams and carbon steel for higher temperature applications.

A HPHE has been applied to exhaust heat recovery for use in steam generator. This system, developed by Q-.DOT Corporation (LITTWIN & MCCURLY, 1981), operates y replacing the lower temperature fluid stream with a water filled pressure vessel. The heat recovered from the exhaust gas is transferred to the pressure vessel; which produces high temperature steam for use in space heating or process reuse. This system is shown in figure. A similar heat pipe waste heat recovery boiler has been has been installed in an oil refinery and the operating parameters are shown in the figure. Typical waste heat recovery boiler system (LITTWIN & MCCURLY, 1981).

CHAPTER 4

HEAT EXCHANGERS

4.1. INTRODUCTION

Increases in the cost of energy have promoted new methods of conserving energy in industrial applications. Due to their high heat transfer capabilities with no external power requirements, heat pipes are being used in heat exchangers for various applications. In the power industry, heat pipe heat exchangers are used as primary air heaters on new and retrofit boilers. The major advantages of heat pipe heat exchangers compared to conventional heat exchangers are that they are nearly isothermal and can be cheaper then conventional tubular heat exchanger because they are smaller and can be shipped in a small number of modules. Heat pipe heat exchangers can serve as compact waste heat recovery systems which require no power, low pressure drop and are easy to install on existing lines. Heat pipe heat exchangers can be categorized into gas-gas, gas-liquid and liquid-liquid type heat units. Among these three, gas-gas heat pipe exchanger consists of a group of externally finned heat pipes, which reclaim waste heat (Groveret al., 1964; Hassan and Accensi, 1973; Holmes and field, 1986; Ivanovskiiet al., 1982). These units eliminate cross-contamination due to the solid wall between the hot and cold gas streams. Also, the heat pipe design is totally reversible (heat can be transferred in either direction). Gas-gas energy recovery units typically fall into three categories: heat recovery in air-conditioning systems (low temperatures), recovery of excess process heat for space heating (moderate temperature), and recovery of waste heat from high temperature exhaust streams for reuse in the process (preheating of combustion air, for example). The units for these applications, but many commercial models are now available utilizing this heat pipe design.

Gas-liquid heat pipe exchangers are less commonly available than gas-gas models due to the fact that the present design of waste heat boilers is very efficient. In the past, exhaust heat from boilers was simply dispersed to atmosphere. Figure 1.20 shows schematics for waste heat recovery with liquid-gas and gas-gas heat exchangers.

Recently, Faghri (1993a) invented an innovative design for a centrifugal heat pipe vapor absorption heat pump (figure1.21). The heat pipes in this heat pump system are disk-shaped with one face partially or completely being the evaporator and the opposite face partially or completely being the condenser

(Faghri, 1994). The wick is designed such that the centrifugal force aids in the delivery of the vapor-absorption heat pump by increasing the heat pumping capacity that can be packaged in a given value, resulting in a more efficient and compact vapor-absorption heat pump system.

The solid model of a finned-tube heat pipe heat exchanger is shown in Fig. 4.1 that gives a general idea of a heat pipe heat exchanger concept.

FIG. 4.1 SOLID MODEL OF A HEAT PIPE HEAT EXCHANGER

Staggered arrangement of tubes is shown in this figure. The upper portion of the heat exchanger is the condenser section while the lower portion is the evaporator, placed in the inlet air duct. The inlet air passes through this staggered bank of tubes. The condenser section is shown above the evaporator because we are using gravity assisted heat pipes.

Data:

- Average outside air temperature: 100.4°F
- Mass flow rate of air: 2.866 lb/sec [Calculated from the data obtained from the Turbocharger Reciprocating Engine Computer Simulation program (Chapman and Keshavarz, 2003)]
- Cross Sectional Dimensions of the inlet air duct: 20 inch × 20 inch

Variable Parameters:

- Surface temperature of heat pipe
- Outlet temperature of air
- Number of heat pipes
- Diameter of heat pipe
- Fin Density

The transverse and the longitudinal pitches that define tube spacing are defined as a direct function of the tube diameter. Also, the diameter of fins is approximated by a function of transverse pitch of the tubes. Thus, the flow area or the spacing between fins of two adjacent tubes is kept constant. This approximation is based on the design specifications for different staggered tube bank arrangements (Kays W. M. and London A. L., 1984). Heat pipe heat exchanger design is analogues to a liquid coupled direct contact heat exchanger. The evaporator and condenser sections can be treated as two separate heat exchangers.

Evaporator:

The evaporator portion of the heat exchanger is a finned tube cross flow (compact) heat exchanger. Standard heat exchanger dimensions are used to determine fin density, other fin parameters, tube pitches in longitudinal and transverse directions. The log mean temperature difference (LMTD) approach was used to solve for unknown variables. As the aim is to increase the air density, the surface temperature of the tubes (heat pipes in this case) and the output temperature of air (cooled air after the heat exchanger) are varied. The flow chart (Figure 10) explains the procedure of the evaporator side design. Initially, the comparison between the values of heat transfer limits of the heat pipe with that of the heat exchanger was done manually (for the best heat exchanger parameters obtained) mainly because the safe heat transfer rate for it was very well above what was required. Therefore, the comparison technique discussed just now is of a little significance but it is found useful for the waste heat recovery application model where there is a close tie between heat transfer capability of heat pipe and actual heat transfer rate required and we need to vary the diameters.

Condenser:

With the given surface temperature, the program calculates the surface temperature at the condenser side of heat pipe. In this case, the system of equations is well defined, unlike the evaporator side exchanger, where the number of unknowns is more than equations so we needed to use a range of data sets and calculate function values such as tube pitch, heat transfer coefficient etc. at specific points.

4.2 HEAT EXCHANGER CLASSIFICATION

In general, heat exchangers can be classified as either regenerators or re-cooperators. In a regenerative heat exchanger, heat is alternately removed from the high-temperature fluid and transferred to low-temperature fluid. The energy transfer which occurs in this type of heat exchanger is dependent on the physical properties of the fluids and heat transfer surface as well as the flow situation of the two fluids. A common type of regenerative heat exchanger is known as the rotary regenerator, which alternately exposes a metal surface to the high and low-temperature fluid streams. While the surfaces are in the high-temperature stream, they absorb heat through conduction into the metallic structure. Then, when the surface is moved into the cold stream, heat is rejected from the metal surface. Rotary regenerators have been used for air-heating applications and flue-gas reheating. An example of a fixed regenerative heat exchanger is the packed porous bed where the high and low- temperature fluids alternately flow through a porous solid. The packed porous bed absorbs heat from the high-temperature fluid and releases the heat to the low-temperature stream as the two fluids cycle through the heat exchanger. While regenerative type heat exchangers often have an efficiency advantage over recuperative types, heat exchangers such as the rotary regenerator require an auxiliary power supply to operate, and are prone to leakage problems between the high- and low-temperature fluids.

In recuperative heat exchangers, the high- and low- temperature fluids do not come into direct contact with each other, but are separated by a solid wall. This type of heat exchanger operates by transferring heat from the high-temperature fluid, through a wall, and into the low-temperature fluid. In which the high- and low-temperature fluids are ducted past each other, separated by a solid wall. Heat is transferred from the high- to low-temperature fluid stream by conduction through the solid wall.

4.3 ADVANTAGES OF HEAT PIPE HEAT EXCHANGERS

A rotary regenerator, plate type, and heat pipe heat exchanger which were designed to operate in the same heat recovery application are compared These three systems were designed to operate with the same high- and low-temperature mass flow rates and physical properties. Implicit to the comparison is the fact that the same that recovery will not be achieved by all three systems. In this table, efficiency is a measure of the heat exchanger performance for the given operating condition, defined as the ratio of the heat transferred by the real heat exchanger to the heat transferred by a heat exchanger performance accounting for size, defined as the ratio of thermal conductance to the volume of the heat exchanger, and the heat-transfer/pressure drop ratio is a measure of the power required to force the high- and low- temperature gas streams through the heat exchanger (Klaschka, 1979).

As can be seen in table 11.1 heat pipe heat exchangers immediately offer the greatest advantage in terms of size reduction. However, there are additional factors which tend to further encourage the use of heat pipe heat exchangers .some of these are:

1. HPHE's have no moving parts or auxiliary power requirements, implying very high reliability.
2. The high- and low-temperature fluid streams are completely isolated in a HPHE, eliminating cross contamination.
3. HPHE's can be designed to be completely reversible: i.e., eat can be transferred in either direction if required.
4. The rate of heat transferred in HPHE can be controlled by adjusting the tilt angle.

5. HPHE's are redundant in design. If one individual heat pipe fails, the heat exchanger is still operational.

6. HPHE's have the capability to operate as thermal transformers. By altering the relative the relative lengths of the evaporator and condenser sections the temperature at which heat is transferred can be controlled.

4.4 HPHE DESIGN

Heat pipe heat exchanger design is a complex problem which involves both quantitative calculations and qualitative judgements. The general design criteria for HPHE's are similar as those for conventional heat exchangers. Heat transfer between the high- and low-temperature fluids and the pressure drop of the fluids as they flow through the heat exchanger core are two major design criteria common between conventional and heat pipe heat exchangers. Detailed design procedures and approaches for conventional heat exchangers are presented by Kays and London (1984) and Rohsenowet al (1985). With heat pipe heat exchangers, the design of individual heat pipes is also a major design criteria with emphasis on working fluid, container selection and heat pipe operating limits. In chapter13, the general design of heat pipes is discussed in detail and in chapter 4 the operating limits are discussed. In this section, design considerations for heat pipes used in heat exchangers are discussed along with the thermal and pressure drop design of HPHE's.

In the design of heat pipe heat exchangers, the configuration of the individual heat pipes is based on several factors, such as the operating temperature range of the heat exchanger, the orientation of the evaporator with respect to the condenser, and the possibility of corrosion of erosion of the heat pipe wall by the high- or low-temperature fluid streams. The operating temperature range of a heat pipe is limited by the working fluid used and is normally between the freezing and critical temperatures of the working fluid. For applications in the HVAC industry, Freons have been used for operating temperatures up to 50°C and water has been used for operating temperatures up to 200°C. At higher operating temperatures organic fluids, such as toluene, naphthalene, and diphenyl-based fluids, and liquid metals such as sodium and mercury, have been used for applications in the power and process industries. Consideration must also be given to the compatibility between the working fluid and container material, so that the working fluid remains chemically stable and does not chemically react with the container material and produce non-condensable gases which will limit the heat transport of the heat pipe. The compatibility of selected working-fluid/container material combinations is given.

For large operating temperature ranges, such as those encountered in preheating combustion air and waste heat recovery from flue gases, where temperature changes between the inlets and outlets of the high- and low-temperature fluids can be 150-200°C, heat pipe heat exchangers are designed with two or more heat pipe working fluids. At the hot side of the heat exchanger, heat pipes with higher temperature working fluids are used, such as naphthalene or diphenyl-based fluids. Then as the high-temperature stream cools, heat pipes with lower temperature working fluids are used such as water or a water/glycol mixture.

Another consideration in the design of heat pipe heat exchangers is the need to protect the heat pipes from temperature extremes above their normal operating temperature range. At these extreme temperatures, high vapor pressures within the heat pipe can cause a rupture of the heat pipe container. To maintain the heat pipe working fluid within allowable temperature ranges, a high – temperature fluid bypass can be used. Also, the heat exchanger can be designed with a much greater mass flow rate of the low-temperature fluid, which will reduce the operating temperature of the heat pipe.

As mentioned before, most neat pipe heat exchangers use thermosyphons, which restricts the orientation so that the condenser is elevated at least 5 above the evaporator, since gravity is used to return the condensate to the evaporator. To prevent local hot spots in the evaporator of thermosyphons, circumferential grooves are used to distribute the working fluid more evenly.

In many heat pipe heat exchanger applications, such as waste heat recovery and combustion air preheating, the heat pipes are exposed to a corrosive environment. Since heat pipes are closed systems, the effects of corrosion over the normal life of the heat exchange need to taken into account for the design of the heat pipe container.

4.5 HPHE APPLICATIONS

In the mid 1970s, HPHE began to be commercially produced. Since that time, numerous applications have been found in many industries. However, HPHE applications can be divided into three main categories:

1. Heat recovery in air conditioning devices
2. heat recovery from the processed exhaust stream to preheat air fro space heating
3. Heat recovery from the process exhaust stream for reuse in the process.

4.6 HVAC APPLICATIONS

Initially, the HPHE's were developed for the HVAC industry because their reliability, reversibility, and freedom from cross-contamination made them highly desirable. HPAC applications can be characterized by near-ambient temperatures and small temperatures differences between the high- and low- temperature fluid streams.

Physically, HPHE's designed for HVAC systems are similar to units designed for other applications. However in HVAC applications extremely high heat transfer coefficients are necessary to offset the relatively low temperature difference between the two fluids streams. Further more the fluids streams in HVAC application are usually clean and free from fouling materials. These two factors imply that HPHE is for HVAC applications need to have external fins with spacing on the order of 5 mm. HPHE is for HVAC applications are typically constructed of aluminium or copper with aluminium external fins.

CHAPTER 5

BILL OF MATERIALS AND COST ESTIMATION

5.1 INTRODUCTION

In this chapter we have arrived at the bill of materials and have also estimated the total cost of implementation of our project. After having analyzed the design of the individual components that make up our system, we can take a decision so as to fabricate or by the components.

The bill of materials for the individual components has been tabulated. Some of the components have been bought depending on their design and availability in the market. The basic structure of our system has been fabricated from scrap metal that was obtained from the market for a nominal price.

Based on the bill of materials, the total cost of implementation of our project has been derived. We have also tabulated the cost calculations for the individual components. The cost incurred by the different machining process has also been listed.

We have estimated the total cost of our project in order to explain its economic feasibility in real time situations. We have also proposed concepts to fully automate this system. Additional costs will incurred so as to implement these concepts. Due to cost cut backs we have only proposed concepts to sophisticate our system.

5.2 BILL OF MATERIALS

Table 5.1 BILL OF MATERIALS

S.No	Part Name	Details	Quantity
1.	Pipe	copper	2
2.	Copper Wire Mesh	Copper	1*1 Sq.Mts.
3.	Spring	Stainless steel	3
4.	Digital Thermo Meter	-50°C to 99°C	1
5.	Relay Contact	_	1
6.	Distilled water bottle	1 liter	2
7.	China dish	Ceramic	2
8.	Wooden stand	Height of 50 cm	2
9.	Burette	1000 ml	1
10.	Polyethylene tube	4 m	-

5.3 COST ESTIMATION

Table 5.2 COST ESTIMATION

S.No	Parts	Material Cost	Labour Cost	Processes
1.	Pipe	900	_	Market Purchase
2.	Copper Wire Mesh	300	_	Market Purchase
3.	Spring	150	_	Market Purchase
4.	Digital Thermo Meter	840	_	Market Purchase
5.	Spring coating	_	40	production
6.	Welding	150	200	_
7.	Relay Contact	400	_	Market Purchase
8.	Copper Vessel	180	_	Market Purchase
9.	Copper Plate	390	_	Market Purchase
10.	Distilled Water Bottle	30	_	Market Purchase
11.	Miscellaneous Expenses	1130	1000	_
	Total	4470	1240	

CHAPTER 6

PRO-E MODELS

HEAT PIPE WITH FINS

FIG. 6.1 HEAT PIPE WITH FINS

END CAP

FIG. 6.2 END CAP

HEAT EXCHANGER MODEL

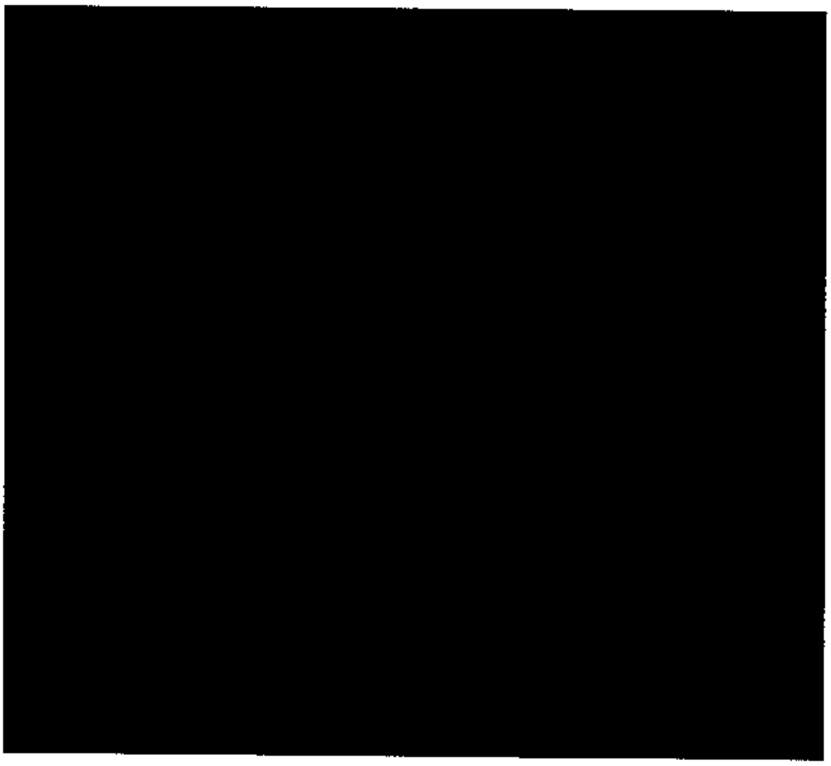

FIG. 6.3 HEAT EXCHANGER

WICK STRUCTURE (FOLDED AND UNFOLDED)

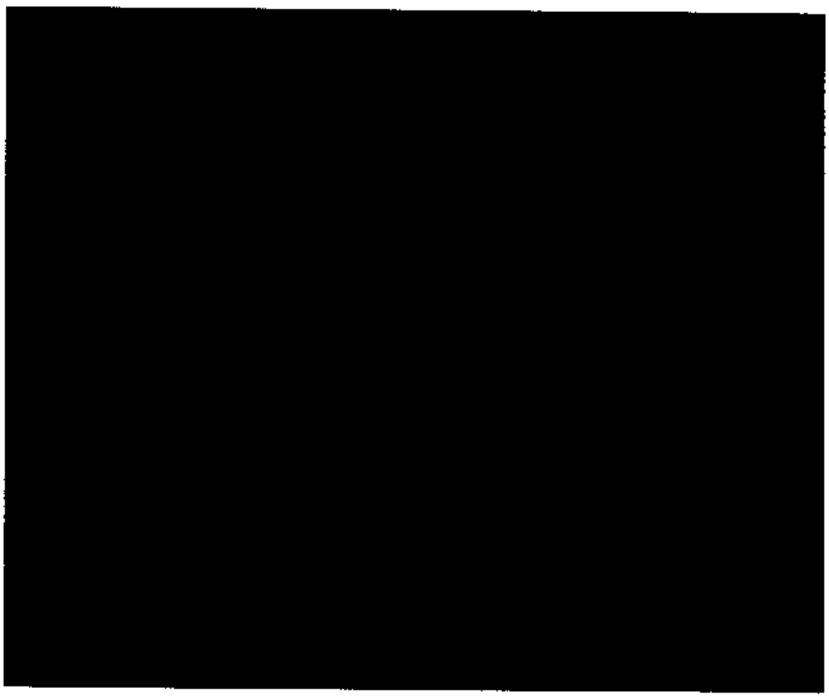

FIG 6.4 WICK STRUCTURE

CHAPTER 7

HEAT PIPE FACRICATION

7.1 DESIGN CONSIDERATIONS

The manufacture of heat pipes involves several procedures which are recommended to be strictly followed in order to achieve the highest quality possible.The three basic components of a heat pipe are:

1. the container
2. the working fluid
3. the wick or capillary structure

1. CONTAINER

The function of the container is to isolate the working fluid from the outside environment. It has to therefore be leak-proof, maintain the pressure differential across its walls, and enable transfer of heat to take place from and into the working fluid.

Selection of the container material depends on many factors. These are as follows:

- Compatibility (both with working fluid and external environment)
- Strength to weight ratio
- Thermal conductivity
- Ease of fabrication, including welding, machine ability and ductility
- Porosity
- Wettability

Most of the above are self-explanatory. A high strength to weight ratio is more important in spacecraft applications. The material should be non-porous to prevent the diffusion of vapor. A high thermal conductivity ensures minimum temperature drop between the heat source and the wick.

2. WORKING FLUID

A first consideration in the identification of a suitable working fluid is the operating vapor temperature range. Within the approximate temperature band, several possible working fluids may exist, and a variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. The prime requirements are:

- compatibility with wick and wall materials
- good thermal stability
- wettability of wick and wall materials
- vapor pressure not too high or low over the operating temperature range
- high latent heat
- high thermal conductivity
- low liquid and vapor viscosities
- high surface tension
- acceptable freezing or pour point

The selection of the working fluid must also be based on thermodynamic considerations which are concerned with the various limitations to heat flow occurring within the heat pipe like, viscous, sonic, capillary, entrainment and nucleate boiling levels.

In heat pipe design, a high value of surface tension is desirable in order to enable the heat pipe to operate against gravity and to generate a high capillary driving force. In addition to high surface tension, it is necessary for the working fluid to wet the wick and the container material i.e. contact angle should be zero or very small. The vapor pressure over the operating temperature range must be sufficiently great to avoid high vapor velocities, which tend to setup large temperature gradient and cause flow instabilities.

A high latent heat of vaporization is desirable in order to transfer large amounts of heat with minimum fluid flow, and hence to maintain low pressure drops within the heat pipe. The thermal conductivity of the working fluid should preferably be high in order to minimize the radial temperature gradient and to reduce the possibility of nucleate boiling at the wick or wall surface. The resistance to fluid flow will be minimized by choosing fluids with low values of vapor and liquid viscosities. Tabulated below(Table 7.1) are a few mediums with their useful ranges of temperature.

TABLE 7.1 VARIOUS WORKING FLUIDS

MEDIUM	MELTING PT. (□ C)	BOILING PT. AT ATM. PRESSURE (□ C)	USEFUL RANGE (□ C)
Helium	- 271	- 261	-271 to -269
Nitrogen	- 210	- 196	-203 to -160
Ammonia	- 78	- 33	-60 to 100
Acetone	- 95	57	0 to 120
Methanol	- 98	64	10 to 130
Flutec PP2	- 50	76	10 to 160
Ethanol	- 112	78	0 to 130
Water	0	100	30 to 200
Toluene	- 95	110	50 to 200
Mercury	- 39	361	250 to 650
Sodium	98	892	600 to 1200
Lithium	179	1340	1000 to 1800
Silver	960	2212	1800 to 2300

3. WICK OR CAPILLARY STRUCTURE

It is a porous structure made of materials like steel, aluminium, nickel or copper in various ranges of pore sizes. They are fabricated using metal foams, and more particularly felts, the latter being more frequently used. By varying the pressure on the felt during assembly, various pore sizes can be produced. By incorporating removable metal mandrels, an arterial structure can also be molded in the felt.

Fibrous materials, like ceramics, have also been used widely. They generally have smaller pores. The main disadvantage of ceramic fibres is that, they have little stiffness and usually require a continues support by a metal mesh.

Thus while the fibre itself may be chemically compatible with the working fluids, the supporting materials may cause problems. More recently, interest has turned to carbon fibers as a wick material. Carbon fibre filaments have many fine longitudinal grooves on their surface, have high capillary pressures and are chemically stable. A number of heat pipes that have been successfully constructed using carbon fibre wicks seem to show a greater heat transport capability.

The prime purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator. It must also be able to distribute the liquid around the evaporator section to any area where heat is likely to be received by the heat pipe. Often these two functions require wicks of different forms. The selection of the wick for a heat pipe depends on many factors, several of which are closely linked to the properties of the working fluid.

The maximum capillary head generated by a wick increases with decrease in pore size. The wick permeability increases with increasing pore size. Another feature of the wick, which must be optimized, is its thickness. The heat transport capability of the heat pipe is raised by increasing the wick thickness. The overall thermal resistance at the evaporator also depends on the conductivity of the working fluid in the wick. Other necessary properties of the wick are compatibility with the working fluid and wet ability.

Variable Parameters:

- Diameter of heat pipe
- Mesh number (for wrapped screen wick)
- Number of layers of wick
- Working fluid and the container material
- Average adiabatic vapor temperature

Assumptions:

- Standard gravity assisted heat pipe. (Condenser placed above the evaporator)
- Steady state operation.
- Turbulent and incompressible vapor flow. (Starting assumption)

7.2 SIMULATION PROCEDURE

Exhaustive search technique was used for finding the optimal parameters for a heat pipe suitable for the given conditions. This procedure involved variation of diameter, mesh number, wick layers and adiabatic temperature over the specified ranges. The mathematical simulation takes into consideration the heat transfer constraints viz. capillary, boiling, entrainment, sonic and viscous limitations, that affect the heat pipe performance. It then finds the optimal values for these parameters which satisfy constraints imposed by the heat transfer limitations. Similar models for different working fluid-container materials were developed to select the most suitable heat pipe under the given conditions. In this selection procedure, the overall temperature gradient for the heat pipe (i.e. temperature difference between evaporator surface and condenser surface) was an important selection criterion along with the better heat transfer rate from the heat pipe. This is because of the fact that the higher temperature gradient generates need for even lower temperature at the condenser, which simply means higher cooling load requirements.

The following is a brief description of the method commonly used in fabricating a heat pipe:

1. Machine the heat pipe container including the pipe wall, end caps, and fill tube, and form the wick structure.
2. Clean the components of the heat pipe of solid particle, oils, and oxides.
3. Assemble the heat pipe using brazing or welding techniques.
4. Leak-check the heat pipe container.
5. Fully instrument the heat pipe with thermocouples, heaters, calorie meters, insulation, etc (for performance testing).
6. Charge the heat pipe with the working fluid.

7.3 HEAT PIPE COMPONENT CONSTRUCTION

There are certain commonly used steps to be considered while fabrication. Each of these steps is examined in the following text in detail.

7.3.1 CIRCULAR CROSS – SECTION HEAT PIPES

In most cases, the geometry of the heat pipes is cylindrical. Therefore, circular cross-section heat pipes are discussed in this section. Most of the information concerning the fabrication of cylindrical heat pipes is applicable to other geometry. A typical heat pipe consists of five components: the container, the wick, the end caps, the filler tube and the working fluid. There is also a multipoint thermocouple probe used to measure vapor temperature during performance testing of prototype heat pipes. The ends of the probe are supported by the end caps so that it does not contact the interiors of the pipe wall. During either brazing or welding, the design shown allows for the introduction of an inert gas i.e. argon, to be passed through the interior of the pipe to reduce oxidation of the wick and the pipe wall. The main body of the hat pipe container can be made from commercially available metallic pipes such as aluminium, copper, mild steel and stainless steel. For applications where the working temperature will be very high, expensive refractory materials such as titanium or tungsten can be used. For low temperature applications, copper and aluminum are the materials of choice, whereas stainless steel is preferable in most high temperature environments. Careful consideration must be given to the possible incompatibility of the materials of the wall, wick, end caps, brazing or welding material, and the working fluid. Problems with chemical reactions, such as the formation of alloys and inter metallic compounds from the solid materials and the fluid, or galvanic action between the different metallic parts must be taken into account. A full discussion concerning this topic is given by Brennan and Kroliczek (1979).

7.3.2 END CAPS

The end caps are designed to provide closure for the container and to provide for the fill tube and instrumentation. There are various end cap designs: butt joint, fillet joint, and internal or external lap joints as shown in figure. In designing an end cap, consideration must be given to the proper thickness ratio at the joint for welding and pressure retention to provide a rupture-proof container. End caps are usually machined with one end cap containing the fill tube.

7.3.3 WICK STRUCTURES

Many types of wick structures are available, such as metal screen, axial grooves, sintered powder, and composite wicks .typically, forming a screen wick involves cutting the proper length and width of screen, and then rolling the screen onto a mandrel. The outer diameter of the rolled-screen/mandrel assembly should be only slightly smaller than the inner diameter of the pipe. Screen wicks made of stainless steel are usually spot welded before being inserted into the pipe, so that uniformity of the thickness can be achieved. Copper and aluminum screen, however, cannot be easily spot welded. Therefore, wicks of copper are tightly wound onto a mandrel, and the residual stress in the rolled screen is normally sufficient to hold it against the inner diameter of the pipe when released from the mandrel. If the residual stress is insufficient to ensure good contact between the wick and the wall, non-uniform annular gaps can be present within the wick. These gaps can be partially beneficial in that the capillary limit is increased, but an accurate calculation of the actual capillary limit and the required fluid charge is very difficult, if not impossible. Therefore, a method for compressing the wick should be used, Such as installing a helical spring within the heat pipe to press the wick against the heat pipe wall. Also, to avoid problems when the end caps are fitted into the end of the, the length of the wick must be carefully trimmed.

The most common types of wicks that are used are as follows:

SINTERED POWDER

This process will provide high power handling, low temperature gradients and high capillary forces for anti-gravity applications. The photograph shows a complex sintered wick with several vapor channels and small arteries to increase the liquid flow rate. Very tight bends in the heat pipe can be achieved with this type of structure.

GROOVED TUBE

The small capillary driving force generated by the axial grooves is adequate for low power heat pipes when operated horizontally, or with gravity assistance. The tube can be readily bent. When used in conjunction with screen mesh the performance can be considerably enhanced.

SCREEN MESH

This type of wick is used in the majority of the products and provides readily variable characteristics in terms of power transport and orientation sensitivity, according to the number of layers and mesh counts used.

7.3.4 WATER PROPERTIES

Water has the desirable properties within the ambient temperature heat pipe range of about 300 and 400 K given by its vapor pressure and merit number. Its vapor pressure in this range is not too high compared to atmospheric pressure. However, at temperatures higher than 400 K, its vapor pressure is much higher as shown in fig. 7.1. With such high vapor pressures, the issues that need to be addressed are the increased thickness of the envelope to advantage in protecting the heat pipe from possible micro-meteoroid impacts while the drawback is the added mass to radiator system. These issues are particularly important for water heat pipes above 500 K, because the vapor pressure in the heat pipe then world be more than about ten times atmospheric pressure.

Commercial copper-water heat pipes used in electronic cooling mostly sintered powder wicks. The heat pipe length varies between 6 in and 18 in depending on the applications. If the heat pipe is long, as is likely in space applications, the wick structure will be an important technology issue. It is difficult to sinter in a long pipe because of the associated problems with mandrel as well as potentially less structural strength in the wick.

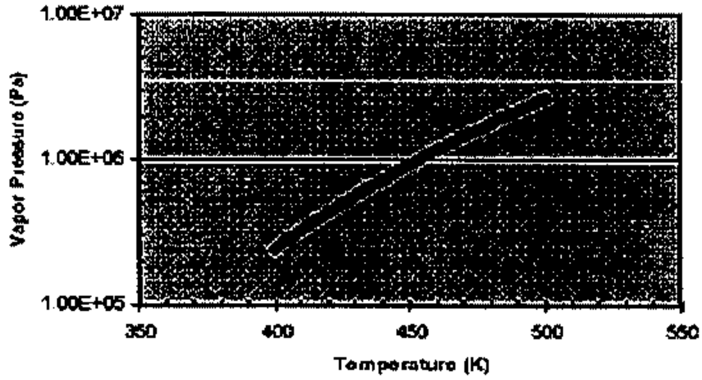

FIG. 7.1 VAPOR PRESSURE OF WATER WITHIN THE INTERMEDIATE TEMPERATURE RANGE.

In the evaluation of potential heat pipe fluids, a useful merit number is defined based on the thermo-physical properties of the fluid (variously called the liquid transport factor and the figure of merit), M, given by (Devarakonda and Anderson, 2005)

$$M = \frac{\rho_l \sigma_l h_{fg}}{\mu}$$

The below figure gives merit number data for water in the intermediate temperature range. Water vary high merit number until about 550 k and then drops off steeply. it appears then worthwhile to explore water as a potential heat pipe fluid up to 550 k by addressing he technology issues as discussed above. In addition, life test data at these higher temperatures need to verify that water is chemically stable, i.e., it does not dissociate or ionize. Long term high temperature thermo-chemical compatibility with envelope and wick metals also needs to be proven.

7.3.5 CLEANING AND DEOXIDIZING

If the interior of a heat pipe is not clean, degradation of the performance can result over time. Solid particles can physically block the wick structure, decreasing the liquid flow rate and increasing the likelihood of encountering the capillary limit. Oils from machining or from the human hand can decrease the wettability of the wick. Oxides formed on the wall and wick can also decrease wettability. Therefore, proper cleaning of all of the parts in contact with the interior of the heat pipe (pipe, end caps, wick, and working fluid) is necessary for maximum reliability and performance. Several steps are needed in order to properly clean the heat pipe container ad wick structure, such as solvent cleaning, vapor degreasing, alkaline cleaning acid cleaning, passivation, pickling, ultrasonic cleaning, and vacuum baking. Many of these steps may be used in a single cleaning operation. The following procedure in recommended for cleaning all heat pipes, except the deoxidizing step is generally not necessary for stainless steel pipes. Instead, a passivating step is done to remove possible iron particles embedded in the stainless steel pipe wall (Edelstein, 1974). If possible, the individual components should be cleaned before assembly and stored in a plastic bag or wrap until needed. If a sealable plastic bag is used, it should be purged of air with an inert gas to avoid oxidation and contamination from the room. The wick should also be cleaned before insertion into the container, unless it is an integral part of the container. If the wick is formed by spotwelding, a nitric acid cleaning may needed to remove copper deposits left by the electrodes. After the wick has been inserted, an alcohol rinse may be used to remove oils due to handling.

7.3.6 SOLID PARTICLE REMOVAL

After degreasing, solid particles are removed from the interior wall of the heat pipe container. This is accomplished by mechanical cleaning in a chlorinated solvent such a trichloroethane or by alkaline cleaning for the removal of oily substances which are insoluble in chlorinated solvents. Alkaline cleaning removes contaminants by detergency, displacement from the surface, rather the solvency, direct solution in the cleaner.

The procedure for cleaning with a chlorinated solvent is as follows:

1. Swab pipe inner surface with disposable laboratory wipes (which do not leave fibers) soaked with 1, 1, 1- trichloroethane. Repeat until wipes exit pipe clean.
2. Rinse for 2 min,. With demonized water.

3. Rinse with methanol to remove the water droplets.
4. Wrap all parts in plastic to prevent contamination prior to final assembly.

7.3.7 HEAT PIPE CONTAINER AND WICK DEOXIDATION

The oxides of aluminium, copper, and stainless steel can reduce the wetting characteristics of a surface which will decrease the capillary pumping capability. To remove these metallic oxides, the heat pipe container, wick and the end caps are deoxidized. After the wick has been inserted into the interior of the container, the assembly is deoxidized by immersion in a deoxidizing agent. For stainless steel, the deoxidation process can be replaced with a passivation process. The deoxidizing agent commonly used for stainless steel is a solution of sodium dichromate (1-4 oz./gal) and nitric acid (15-30% by volume). For copper and aluminium heat pipes, the deoxidizing agent commonly used is a solution of sodium dichromate (2-6 oz. /gal) and sulfuric acid (4-7% volume). A deoxidation procedure for copper heat pipe is outlined below:

1. Place the heat pipe assembly and the end caps in a liquid deoxidizer (sodium dichromate, 6 oz./gal; sulfuric acid, 7% by volume; deionized water) for 30 min.
2. Rinse all parts in deionized water for 5 min.
3. Rinse all parts in methanol to remove water and prevent spotting.

7.3.8 LEAK DETECTION

Prior to charging the heat pipe, it must be verified that the container is free from leaks. Several methods are available which can detect leaks of different magnitudes. Very large leaks can e found by filling the container with compressed nitrogen gas and painting the surface with soap solution. Smaller leaks are noticed when the pipe cannot be pumped down sufficiently with roughing pump to engage a high-vacuum pump. Still the smaller leaks will cause the pressure within the high-vacuum pump too not reach its ultimate capacity. Therefore, a series of procedures is needed to determine the magnitude of the leak, and then the location of the hole in the container. The magnitude of the leak will be quantified by the pressure seen in the leaking pipe if attached to a vacuum system, instead of the standard volume of air per second (std cm3/s). This is done since most experiments have access to vacuum equipment, but do not have a leak rate measurement system. With this method, the pressure inside containers with gross leaks ranges from the atmospheric to 1 torr, low-vacuum leaks range from 1 torr to 10-3 torr, and high –vacuum leaks range from 10-3 to 10-9 torr.

7.3.9 HEAT PIPE EVACUATION AND CHARGING

In order to prevent non-condensable gases from entering the heat pipe during the charging process, a suitable evacuation/filling rig must be used. The rig must be able to evacuate the container to 10-7 torr. The filling rig is used to evacuate the pipe and charge it with the proper amount of working fluid. All the cryogenic and some low-temperature working fluids exist as a gas at room temperature, so the heat pipe container and filling fluids exist as a gas at room temperature, so the heat pipe container and the filling rig must be able to withstand high internal pressures. Low-temperature working fluids such as water, methanol and acetone are in liquid state at room temperature so charging is relatively simple. High-temperature working fluids however are in solid state, so special procedures must be employed, which include prevention of fire due to the reaction of some liquid metals with water and humidity in the air.

7.4 HEAT PIPE PERFORMANCE TESTING

After the successful processing, it is necessary to perform experiments to determine the performance specification and heat transport limitations of the heat pipe. For low-temperature heat pipes, the most readily encountered limit is the capillary limitation, where the amount of condensate returning to the evaporator section is insufficient to prevent the dry out of the evaporator. This phenomenon is accompanied by sudden increase in the temperature difference between the evaporator end cap and the adiabatic section. Since this temperature increase will usually become steadily greater, performance testing must be halted at this point, and the heat pipe be allowed to return to its initial temperature. The sonic limit is found in the operation of the high temperature heat pipes, in which a steep temperature difference front moves down the length of the heat pipe during the startup. If the heat input at the evaporator is high enough, the front will reach the condenser cap, at which time the heat pipe will approach isothermal operation. The frozen startup limit (FSB) can also be reached during the startup of high-temperature heat pipes, where the vapor travels down the length of the heat pipe, and is frozen onto the wick in the condenser and adiabatic sections. This prevents the return of the condensate to the evaporator, leading to dry out. Typical testing procedures for ow- and high-temperatures are discussed below.

7.5 LOW TEMPERATURE HEAT PIPES

Low temperature heat pipes are normally tested for the capillary limit by slowly increasing the amount of heat input to th pipe, as follows: after the heat pipe has been set to the proper elevation, the heater is turned on with a low power input compared to that which is predicted by the analytical methods. As the working temperature (middle of the adiabatic section) increases, the cooling water is started and adjusted to maintain a given working temperature, if a water cooled calorie meter is used. The heat pipe is allowed to reach the steady state, which can be monitored by plotting several temperatures on the pipe. The time necessary to reach the steady state varies with the size of the heat pipe, the thickness of the wall and wick, and the amount of insulation. The temperatures of the heat pipe and the inlet and the outlet of the calorie meter are recorded, as well as the power input and the coolant mass flow rate. Then, the power input is increased by sufficiently small steps until dry out occurs. Once the dry out limit is reached, the power must be reduced until the pipe becomes isothermal. In composite wick designs, where repriming of the wick may be more difficult, the power must be completely halted and the elevation of the pipe may need to be reduced.

7.6 HIGH TEMPERATURE HEAT PIPES

Extreme caution must be used in the design of a testing facility for high temperature heat pipe, since the operating temperature range from 500 -1200C. Also, a potential explosion hazard may exist for working fluids such as sodium due to the exothermic reaction with after or even humidity in air. To avoid personal injury, high temperature performance testing is usually carried out in stainless steel vacuum chamber. In this way, not only will the explosion hazard be minimized by the operation of vacuum, but any working fluid leak will be contained within the chamber, and not be released to the environment.

The testing procedure for high-temperature heat pipes is as follows: The heat is input in the evaporator at a level sufficiently below both the capillary and the frozen limits. If the heat pipe is started at the room temperature, the working fluid must be melted before operation can begin. Therefore, a high temperature front will move down the length of the heat pipe as frozen startup progresses. If the heat input is not sufficient, the front will stop in the condenser section, and a steady state condition will be attained. Further increases in the heat input will force the front to the condenser end cap. After this point, the heat pipe temperature will become nearly isothermal. Increasing the heat input in steps will eventually lead to capillary limit.

7.7 TESTING OBSERVATION

The experimental setup was placed in the R&AC laboratory. The three pipes were tested. The heat pipes one at a time were positioned at four different angles to see the working conditions at different positions. The four inclination angles are 90, 60, 45 and 30 deg. The heat pipes were held using a wooden stand so as to reduce the heat conduction. As the pipes were held on the wooden stand, it was dipped in a water bath. The bath was so placed so that the heat transfer to the heat pipe was to the evaporator section of the heat pipe, a few centimeters above the end cap. The heat was supplied by an electric heater. Constant heat supply was maintained with the help of instrumentation. A relay was used and a sub zero digital thermometer which has a probe to measure the temperature of the water bath was used. The temperature limits are set in the digital thermometer. The temperature limit is so set in the sub zero thermometers such that only constant heat is supplied to the water bath. Once the water temperature goes beyond the set temperature the heat to the water bath is cut off. The readings are taken when the limit is reached. Temperature is noted using a digital thermometer at the evaporator section, the adiabatic section, below the cooling fins and after the cooling fins. Once the temperatures are noted the temperature limit in the sub zero is changed to an upper limit. Once again the temperatures are noted at different regions of the heat pipe. This is repeated for different temperature limits in the subzero. The position of the heat pipes are changed for various angles and the experiment was repeated. All the three pipes were tested in the same manner. All the experimental values were tabulated to let us decide on to which one of pipes is a best suitable one for heat recovery.

Thus three heat pipes are fabricated in this projected and experiments were conducted on the heat pipe to study its working. Experimental values are produced, graphs produced for them and calculations pertaining to the heat pipes were done. Also a 3D-graph was drawn with SYSSTAT software. After observations from the experiments the best and optimal heat pipe for heat recovery was selected. The heat was recovered from the exhaust of a diesel engine using the heat pipe. The working temperature of the heat pipe specific to the application was determined.

SPECIFICATION OF HEAT PIPE

- Pipe Material = copper.
- Length of the pipe = 850 mm.
- Inner dia of the pipe = 22mm
- Outer dia of the pipe = 25.4 mm
- Wick material = copper
- Wick structure type = screen mesh(160 mesh)
- Fluid used = distilled water
- Volume of the liquid = 50 ml
- Heat transfer capacity:

  Max heat transfer = 2.85 kW

  Min heat transfer = 0.08 kW

  Operating temp = 65°c to 100

SPECIFICATION OF HEAT PIPE 2

- Pipe Material = copper.
- Length of the pipe = 500 mm.
- Inner dia of the pipe = 22mm
- Outer dia of the pipe = 25.4 mm
- Wick material = copper
- Wick structure type = screen mesh(160 mesh)
- Fluid used = distilled water
- Volume of the liquid = 30 ml
- Heat transfer capacity:

  Max heat transfer = 3.0 kW

  Min heat transfer = 1.2 kW

  Operating temp = 55°c to 85°c

SPECIFICATION OF HEAT PIPE 3

- Pipe Material = copper.
- Length of the pipe = 35 mm.
- Inner dia of the pipe = 22mm
- Outer dia of the pipe = 25.4 mm
- Wick material = copper
- Wick structure type = screen mesh(160 mesh)
- Fluid used = distilled water
- Volume of the liquid = 20 ml
- Heat transfer capacity:

  Max heat transfer = 3.0 kW

  Min heat transfer = 1.5 kW

  Operating temp = 55°c to 75°c

The specification of the heat pipe is shown above. The pipe material is made up of copper. The conductivity of this copper is 0.9. The length of the copper pipe is taken for three samples as 850mm, 500mm, 300mm. From the measurements it is found that the pipe has an inner diameter of 22mm and the outer diameter is 25.4mm. The heat transfer capacity is the operating temperature is 65°C and the maximum limit is 100°C.Here the fluid used is distilled water. The proportion of distilled water used for three pipes are 50 ml,30ml,20 ml respectively for 850 mm, 500mm, 300mm. Here the wick material used is copper and is of the type screened wick the mesh number is 160.

Tabulation-1

Length of the pipe = 850 mm

Angle of inclination of pipe axis from horizontal = 90 deg.

TABLE 7.2 TABULATION 1

Water temperature.	Evaporator temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	Top
52	46	42	38	36
60	52.7	50.5	38.5	37.5
70	60	57	49.5	41
80	65.2	64	60	45
90	69.4	67.8	63	47

The table 7.2 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 850 mm and its axis is inclined at an angle of 90 degree with the horizontal plane.

Tabulation-2

Length of the pipe = 850 mm

Angle of inclination of pipe axis from horizontal = 60 deg.

TABLE 7.3 TABULATION 2

Water temperature.	Evaporator temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	Top
37	36.1	35	35	34.5
57.1	42.1	41.3	41.6	42
60	44.3	43.1	40.5	43.4
68.3	50	48.8	45.2	49.5
72	52	51.7	47.2	51.8
81	65.3	60	47.9	54.2

The table 7.3 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 850 mm and its axis is inclined at an angle of 60 degree with the horizontal plane.

Tabulation-3

Length of the pipe = 850 mm

Angle of inclination of pipe axis from horizontal = 45deg.

Table 7.4 TABULATION 3

Water temperature.	Evaporator temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	Top
50	45	34	34	34
60	48.1	36	36	35
70	59.5	47.3	38	35
80	64.2	54.1	42.4	35
90	75	80.3	50.2	35.

The table 7.4 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 850 mm and its axis is inclined at an angle of 45 degree with the horizontal plane.

Tabulation-4

Length of the pipe = 850 mm

Angle of inclination of pipe axis from horizontal = 30deg.

TABLE 7.5 TABULATION 4

Water temperature.	Evaporator temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	Top
54	48	36.6	33	32.3
62	55.1	37.3	33	32.3
74	63.1	39.5	33	32.3
82	69.6	58.5	38	34
94	83	86	52.2	38.7

The table 7.5 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 850 mm and its axis is inclined at an angle of 30 degree with the horizontal plane.

Tabulation-5

Length of the pipe = 500 mm

Angle of inclination of pipe axis from horizontal = 90 deg.

TABLE 7.6 TABULATION 5

Water temperature.	Evaporator temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	Top
50	43.7	43.6	43.6	41
60	50	49.5	48.5	44.4
70	57.4	55.6	55.1	50.3
80	62.3	62	59.1	56
90	80.2	69.3	65.4	59

The table 7.6 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 500 mm and its axis is inclined at an angle of 90 degree with the horizontal plane.

Tabulation-6

Length of the pipe = 500 mm

Angle of inclination of pipe axis from horizontal = 60 deg.

TABLE 7.7 TABULATION 6

Water temperature.	Evaporator temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	Top
50	45.6	44.2	44.6	40.8
60	50.8	49.3	49	47.1
70	57.6	56.3	55.1	52
80	68.2	66.7	65.3	57
90	76.7	72.8	68.2	59.4

The table7.7 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 500 mm and its axis is inclined at an angle of 60 degree with the horizontal plane.

Tabulation-7

Length of the pipe = 500 mm

Angle of inclination of pipe axis from horizontal = 45deg.

TABLE 7.8 TABULATION 7

Water temperature.	Evaporator. Temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	top
50	48.3	47.8	47	42.3
60	59.1	57	56.5	52.3
70	64.4	58.1	57	54
80	69.1	65.3	64.5	59

The table 7.8 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 500 mm and its axis is inclined at an angle of 45 degree with the horizontal plane.

Tabulation-8

Length of the pipe = 500 mm

Angle of inclination of pipe axis from horizontal = 30deg.

TABLE 7.9 TABULATION 8

Water temperature.	Evaporator. temperature.	Adiabatic temperature	Condenser temperature	
			Bottom	top
50	47.5	46.2	45.5	45
60	53.4	52	51.2	50.6
70	62.1	59.3	57.9	57
80	63	62	61.8	60.6

The table 7.9 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 500 mm and its axis is inclined at an angle of 30 degree with the horizontal plane.

Tabulation-9

Length of the pipe = 300 mm

Angle of inclination of pipe axis from horizontal = 90 deg.

TABLE 7.10 TABULATION 9

Water temperature.	Evaporator. temperature.	Adiabatic temperature	Condenser temperature	
			Bottom	top
50	48.4	47	46.3	43.5
60	57.5	56.8	56.8	53.4
70	62.3	61.5	61	57.4
80	65.7	62.4	62.4	60.9

The table 7.10 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 300 mm and its axis is inclined at an angle of 90 degree with the horizontal plane.

Tabulation-10

Length of the pipe = 300 mm

Angle of inclination of pipe axis from horizontal = 60 deg.

TABLE 7.11 TABULATION 10

Water temperature.	Evaporator. temperature.	Adiabatic temperature	Condenser temperature	
			Bottom	top
50	44.4	43.7	40.1	39.1
60	50.5	49.4	46.6	44.2
70	54.6	54.4	53	50.7
80	63.3	61.2	58	55.9

The table 7.11 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 300 mm and its axis is inclined at an angle of 60 degree with the horizontal plane.

Tabulation-11

Length of the pipe = 300 mm

Angle of inclination of pipe axis from horizontal = 45 deg.

TABLE 7.12 TABULATION 11

Water temperature.	Evaporator. temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	top
50	45.1	42.6	41	39.5
60	49.7	45.3	44.3	42.3
70	56.5	55.5	55.8	50.3
80	64	62.6	61.8	58.4

The table 7.12 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 300 mm and its axis is inclined at an angle of 45 degree with the horizontal plane.

Tabulation-12

Length of the pipe = 300 mm

Angle of inclination of pipe axis from horizontal = 30 deg.

TABLE 7.13 TABULATION 12

Water temperature.	Evaporator temperature.	Adiabatic temperature.	Condenser temperature	
			Bottom	top
50	47.6	45.8	41.2	39.2
60	56.1	55.6	51.3	48.3
70	62.2	60.1	55.3	52.3
80	63.7	63.5	63.3	59.7

The table 7.13 shows the various temperatures measured in the different sections of the heat pipe. The length of the pipe is 300 mm and its axis is inclined at an angle of 30 degree with the horizontal plane.

CHAPTER 8

CHARACTERISTIC CURVES

8.1 FIGURE OF MERIT

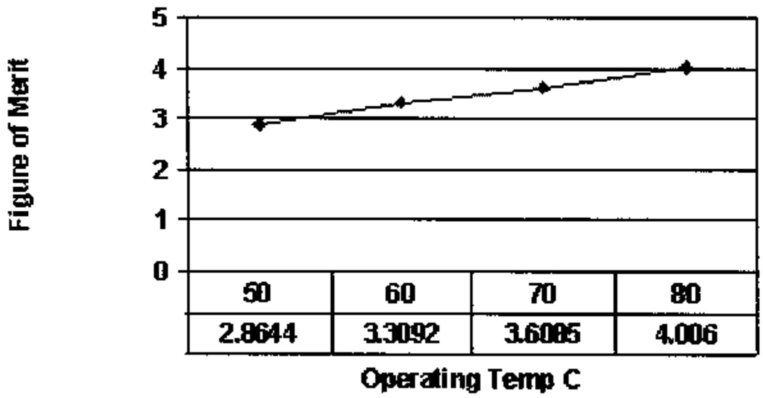

FIGURE 8.1 FIGURE OF MERIT

$$\text{Figure of merit} = \frac{\rho_l \sigma_l h_{fg}}{\mu}$$

Where,

ρ_l - density of the vapor (kg/m^3)

h_{fg} - latent heat of the liquid.(KJ/Kg.K)

σ_l - surface tension of the liquid (N/m^2)

μ - Vapor viscosity (Ns/m^2)

The figure of merit is just a dimensionless factor used to compare the heat pipes of different specifications. Heat pipe with higher merit number can transport heat with heat loss. From the fig 8.1 the copper water heat pipe has higher figure of merit at 80C. Hence it can operate safely at higher operating temperature.

8.2 SONIC LIMIT

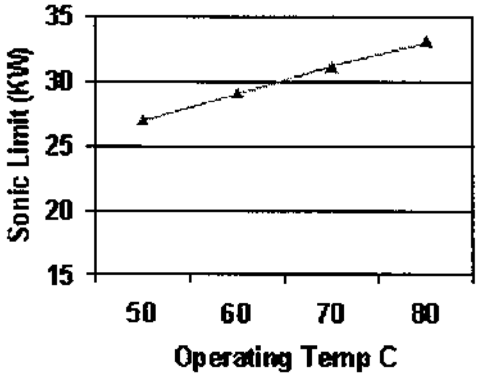

FIGURE 8.2 SONIC LIMIT

Heat transfer limit for sonic limitation, $Q=\Pi * r_v^2 * \rho * h_{fg} \sqrt{(\gamma * R * T_v/(2(\gamma+1)))}$

Where,

Q - Heat transfer limit for sonic limit.(w)

r_v - radius of the vapor surface (m)

ρ - Density of the liquid, (kg/m^3)

h_{fg} - latent heat of the liquid. (KJ/Kg K)

R - Fluid gas constant (KJ/Kg K)

T_v - temperature of the vapor (K)

γ - Specific heat ratio.

The sonic limit usually occurs during the heat pipe startup or during the steady state operation when the heat transfer co-efficient at the condenser is high. The sonic limit is usually associated with liquid–metal heat pipes due to high vapor velocities and low densities. When the sonic limit is exceeded, it does not represent a serious failure, as does the capillary limit. The sonic limitations corresponds to a given evaporator end cap temperature. From the fig. 8.2 the water heat pipe has higher sonic limit at higher operating temperature.

8.3 DEGREE OF SUPERHEATING

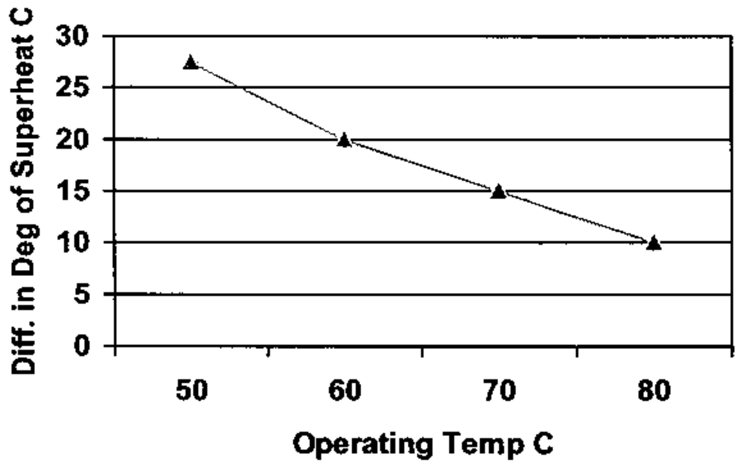

FIGURE 8.3 DEGREE OF SUPERHEAT

Degree of Super Heat

$$\Delta Ts = \frac{3.06 * \sigma * Tv}{\rho v * h_{fg} * \delta}$$

Where,

σ - Surface tension of the liquid (N/m^2)

T_v - temperature of the vapor (K)

ρ_v - density of the vapor , (kg/m^3)

h_{fg} - latent heat of the liquid. (KJ/Kg K)

δ - boundary layer thickness ,(mm)

The degree of super heat indicates the boiling of liquid inside the pipe. Heat pipes with higher degree of super heat are more preferable. From the fig.8.3 the copper water heat pipes have higher degree of super heat at lower operating temperature.

8.4 ENTRAINMENT LIMIT

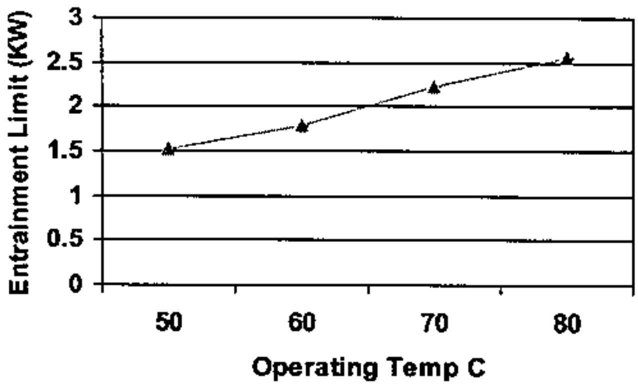

FIGURE 8.4 ENTRAINMENT LIMIT

A shear force exists at the liquid-vapour interface since the vapor and liquid move in opposite directions. At high relative velocities, droplets of liquids can be torn from the wick surface and entrained into the vapor flowing towards the condenser section. If the entrainment becomes too great, the evaporator will dry out. The heat transfer rate at which this occurs is called the entrainment limit. From the fig. 8.4, the cu-H_{10} heat pipe has higher entrainment limit at higher operating temperatures. From the fig. the copper water pipe has higher entrainment limit at higher operating temperature.

8.5 LIQUID TRANSPORT FACTOR

Ne = Surface tension * Latent heat per unit volume/ absolute viscocity

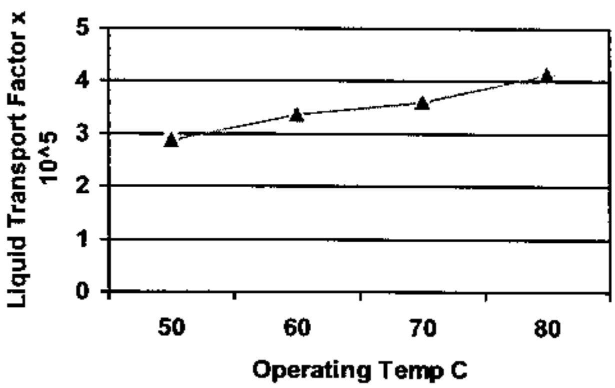

FIGURE 8.5 LIQIUD TRANSPORT FACTOR

The copper water heat pipe has higher liquid transport factors at higher operating temperatures. From the characteristic curves fig.8.5 it can be inferred that the copper water heat pipe can be effectively used at higher operating temperature.

8.6 EFFECT OF ANGLE OF INCLINATION

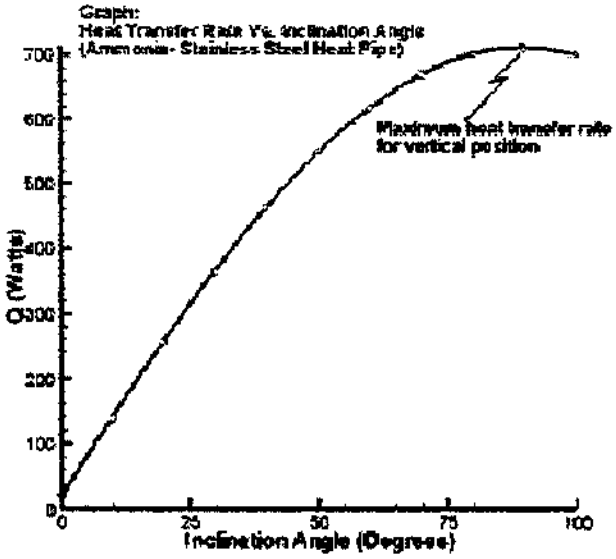

FIGURE 8.6. EFFECT OF INCLINATION ANGLE ON HEAT PIPE PERFORMANCE

The effect of inclination angle on heat pipe performance is illustrated in Fig. 8.6 when the heat pipe is at 0° with the horizontal, then the heat transfer rate is considerably less. The heat transfer rate increases with the angle of inclination and reaches the maximum at 90°C Although the heat transfer rate can be increased with advanced wick structures and layers, the graph only compares performance with different inclination angles. The container must withstand the vapor pressure of the inside working fluid. The most widely used design technique for the heat pipe container material is the American Society of Mechanical Engineers, (ASME) code for unfired pressure vessels (Section VIII, division I (American Society of Mechanical Engineers, 2001). The ASME code specifies that the maximum allowable stress at any temperature be one-quarter of the materials ultimate tensile strength. An initial thickness is assumed and output from the programs used to calculate the hoop stress developed. The result is cross-checked with the permissible hoop stress value and the design is safe. A similar procedure is used for the waste heat recovery heat pipes.

From the above analysis, the safe design values for the heat pipes to be used as a HPHE is to be obtained and it is as follows:

- Inner Diameter of heat pipe : 1.062 inch
- Outer Diameter of Heat pipe: 1.22 inch
- Mesh Number for wick : 60 per inch
- Number of wick layers: 1
- Average adiabatic vapor temperature: 48°F (282 K)
- Temperature drop along the length of heat pipe: 16°F (10 °C)

8.7 SPECIFICATION OF HEAT PIPE HEAT EXCHANGER

- Drum material = Zinc
- Inner dia of the drum = 12.5cm
- Outer dia of the drum = 12.8cm
- Height of the vessel = 20.5 cm
- Inlet pipe

  Inner dia =0.9cm

  Outer dia =1.2 cm

DESCRIPTION

The heat exchanger is designed so that the water inlet is kept at bottom of the vessel and the outlet is kept at top of the vessel. Known quantity of the water is passed at the inlet and comes at the outlet recovering waste heat at condenser end. By varying the flow rate the heat tecovery rate can be varied.the experiment is conducted for loads of 0 , 6 , and 12 kg and for flow rates of 0.5lpm, 1.5lpm, 2.5lpm.

CHAPTER 9

DESIGN OF EXPERIMENTS

"Design of Experiments" refers to experimental methods used to quantify indeterminate measurements of factors and interactions between factors statistically through observance of forced changes made methodically as directed by mathematically systematic tables. A Design of Experiment (DOE) is a structured, organized method for determining the relationship between factors (Xs) affecting a process and the output of that process (Y).It is used for conducting and analyzing controlled tests to evaluate the factors that control the value of a parameter or group of parameters.

9.1 THE NEED FOR DESIGNED TESTS

- When theory is unknown or inadequate
- When the risk is high
- There are a lot of unknowns
- For new products
- When other people are not convinced

If we can understand the underlying mechanism inherent in a system and can formulate a model between design and response variables, then we may not need a designed test. But this is usually not the case. Using DOE results in empirical models being developed which are more than adequate as replacements for theoretical models.

When the risk of making incorrect product decisions is high we need DOE. For example, when making a change to a profitable product we usually want concrete evidence that the change is for the better. Using DOE is like taking out an insurance policy against making bad product decisions.

DOE is especially useful when making decisions involving a lot of unknowns. For example, when developing a new product there are usually a lot of unknowns about how best to design the product. DOE can turn unknowns into accurate estimates of the effects of variables. Many times people involved in product development need to be convinced that a certain direction is best. These people require hard evidence on which to base decisions. They are not willing go forward on the basis of product expert's recommendations. A properly designed test will convince the skeptics of the best course of action.

9.2 DESIGN AND RESPONSE PARAMETERS

TABLE 9.1 TERMS AND SYNONYMS

(1)	(2)
Design Variables	Response Variables
Controlled	Measured
Independent	Dependent
Factors	Characteristics
Input	Output
Recipe	Attributes
Knobs	Parameters

The terms in column (1) table 9.1 are synonyms as are the terms in column (2). Design variables are the variables we have control over. Response variables are the variables we can't control but can measure. Typically we want to achieve certain values of Response variables by manipulating the levels of Design variables. Examples of Design variables include weight, size, % ingredients, processing settings such as time and temperature. Examples of response variables include consumer acceptance measures, quality measures, purity, yield, cost, tensile strength. The distinction between design and response variables can be blurred. If two variables are highly correlated and can't be varied independently, then it is best to chose one as a design variable and measure the other as a response variable.

9.3 THE IMPORTANCE OF DOE

Finagle's 2nd law:

No matter what the experiment's result, there will always be some eager to:

Misinterpret it

Fake it

or Believe it supports his own pet theory

9.4 STEPS IN USING DOE

1. Plan test for DOE
2. Choose design variables and the test range of each
3. Decide which variables to hold constant
4. Select the measured response variables to include
5. Select a statistical test design
6. Run the test *(build test items and gather data)*
7. Analyze data by computer – develop models
8. Interpret computer results
9. Make recommendations
10. Build verification products

9.5 ADVANTAGES OF DOE

1. DOE eliminates the 'confounding of effects' whereby the effects of design variables are mixed up. Confounding of effects means we can't correlate product changes with product characteristics.

2. DOE helps us handle experimental error. Any data point may contain bad data, i.e. is

- Accurate to only +/-? %.
- Experimental Error
- The effects of variation in:
- Raw Materials
- Test Instruments
- Machine Operators

3. DOE helps us determine the important variables that need to be controlled.

4. DOE helps us find the unimportant variables that may not need to be controlled.

5. DOE helps us measure interactions, which is very important

CHAPTER 10

TESTING AND DISSCUSSION

10.1 DEVELOPING THE DESIGN MATRIX

A three level, two- factors, central composite rotatable factorial design (Cochran and Cox 1963)) consisting of 13 sets of coded conditions are shown in Table 10.1. All input variables at the intermediate level (1) constitute the central points and the combination of each of the variables at its lowest level (0) or highest level (2) constitutes the star points.

TABLE.10.1 DESIGN MATRIX AND OBSERVED VALUES OF PERFORMANCE PARAMETERS

S.No	Load Kg	Mass Flow Rate Lpm	Heat Pipe Heat Recovery Rate (kw)
1	0	0	0.80
2	0	2	1.39
3	2	0	1.57
4	2	2	1.95
5	2	1	1.51
6	0	1	1.69
7	1	0	1.07
8	1	2	2.61
9	1	1	2.69
10	1	1	2.75
11	1	1	2.81
12	1	1	2.83
13	1	1	2.85

The experiments were conducted as per the design matrix at random to avoid the possibility of systematic errors infiltrating the system. The 13 experimental runs allowed the estimation of the linear, quadratic and two way interactive effects of the input variables on the HRR. The HRR is calculated using equation

$$Q = m\, C_p\, \Delta T$$

10.2 DEVELOPMENT OF MATHEMATICAL MODELS

The responses can be expressed as a function of *F (Tc, Te)* and their second order interactions can be expressed as

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta 1 1 X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2$$

In equation (7) Y represents any of the responses, X_1 and X_2 represents the coded values of evaporator and condensing temperatures. The coefficient β_o, β_1, β_2 β_{11}, β_{22} are the regression coefficients to be determined. The β parameters can be calculated by the method of least squares where the basic formula is as follows.

$$B = (X^T X^{-1}) * X^T Y \qquad (8)$$

In the equation (8) B represents the column vectors of the estimated parameters, X represents the calculation matrix, X^T represents the transportation matrix and $X^T Y$ represents the variance matrix.

10.3 EVALUATION OF THE COEFFICIENTS OF MODELS.

The values of the coefficients were calculated by using Quality America – DOE PC IV, software package (DOE-PC IV software reference manual 1998). The values of regression coefficients give an idea as to what extent the input variables affect the responses quantitatively. Insignificant coefficients were dropped along with the parameters with which they are associated, without affecting the accuracy of the models very much. This was carried out by conducting backward elimination analysis with t- test probability criterion kept at 0.75. The significant coefficients were recalculated and the final mathematical model is developed using only these significant coefficients. The final mathematical model in coded form as determined from the above analysis is represented below.

$$Y = 0.649 + 1.724X + 1.410Y - 0.736X^2 - 0.496Y^2$$

X→ load(kg)

Y→ mass flow rate(lpm)

10.4 OPTIMIZATION OF HEAT PIPE HEAT EXCHANGER

10.4.1 SYSTAT- INTRODUCTION

SYSTAT offers a large number of scientific and technical graphing options and a great deal of interactivity for a desktop statistics package. Compare subgroups, overlay charts, transform coordinates, and add geographic projections, change colors, symbols and more to create insightful presentations. Change graph locations, point-and-click to alter axis labels, scales, colors and symbols. Create unique graphs that bring out the true meaning in your data with advanced chart options including normal and kernel densities, multiplots, maps, Voronoi tessellations, function plots, contours, scatter plot matrices with 20 diagonal density choices and 126 non-parametric smoothing options, just to name a few. Analysis can be done at a faster rate by rotating your 3-D graphs to visually determine the perfect power or log transformation to normalize your data using the Dynamic Explorer. Create insightful presentations with advanced chart types such as maps, multiplots and kernel densities. Analysis with SYSTAT's interactive graphic tools is really interesting. Simply point-and-click to perfect to the graph's appearance.

Thus by using systat a final graphical surface generation can be done for which a program has to be written and fed into the systat software, for which Annova regression is done and the equations are generated. These equations are used in a program written for Systat. The program is similar to a normal program written for a CNC machine or a numerical controlled machine but it involves expressions and parameters like fplot, facet, zlab, xcuy, zmin, facet and many others. Using these equations and expressions a final program is written to generate a surface so the final comparison can be done effectively between the Z fin and the Straight fin radiator. Hence Annova regression plays a major role in the generation of an equation, program and thereby helps in surface generation. The programs for temperature difference and Heat rejection rate for the radiators in thus written.

10.4.2 SYSTAT SOFTWARE

SYSTAT 10.2 is one of the most powerful statistical and graphical analysis packages now on the market. SYSTAT is a comprehensive statistical software package for analyzing data and presenting results. It is set up in a graphical environment and most commands can be executed by using menus and selecting options in dialog boxes. While some may think Microsoft's Excel provides all the data graphing capabilities they will ever need, many computer users regularly need more powerful statistical analysis capability than is built into Excel. Businesses with a major commitment to quality control and continuous improvement require constant sampling of their product specifications to produce data that must be diligently managed by a team of engineers and other staff with the technical skills and knowledge to accurately perform these tests and correctly interpret the results. A spreadsheet alone cannot meet the needs of these professionals. Instead, they turn to highly specialized, powerful statistical analysis packages.

Professionals involved in medical research also need such powerful software to handle the research tools and techniques that are essential in being able to make carefully reasoned decisions based on data produced in their testing processes. In addition, higher level students will likely find themselves regularly involved in the design and implementation of research projects, and they too need SYSTAT to help them with the important statistical analysis of the results of the data gathering phase of their project. This analysis of research data is a good example of how important it is to integrate specialized statistical analysis software programs in these organizations and for these purposes. This is where the SYSTAT 10.2 program will provide the quality tool needed by these sophisticated computer users.

10.4.3 ENHANCEMENT OF SYSTAT

Windows 2000 support

Command File Editor

Ridge Regression

Rank Regression

Post-hoc Tests for Repeated Measures

N-tiles and Percentiles

Basic Statistics for Cross Tabulations

Excel Import

10.4.4 INCREASE YOUR ANALYTICAL POWER

With SYSTAT, there is no need to worry about finding the right statistic to use in your data analysis. Robust algorithms from leading statisticians give meaningful results to your analysis, even with extreme data. You can fit regression models in nested, 2-level data when assumptions of independent observations are violated and the estimates from standard least squares general linear model (GLM) are suspect. You can create missing value estimates using regression-based point estimation or an EM algorithm, and then save the data or the triangular matrix as input to GLM, ANOVA or other models.

Analysis geostatistical data with deep spatial statistics capabilities, including 2-D and 3-D images. Obtain complete distributions and standard errors using SYSTAT's bootstrapping capability implemented globally across 21 statistical procedures, even when normality assumptions are violated and no model is available.

10.4.5 GET MEANINGFUL RESULTS WITH LESS EFFORT

Being really tired of extravagant user interfaces slowing down? Stalled by difficult programming languages? SYSTAT's intuitive Windows interface and flexible command language are designed to make research more efficient.

It is easy to locate advanced options through clear, comprehensive dialogs. Type commands directly into SYSTAT's interactive command window to fly through your analyses. Quickly navigate through detailed results using the browser-style Output Organizer. Dramatic changes are made in analysis with new keystrokes.

SYSTAT's command language is interactive, powerful, and easy to learn written commands using plain English with minimal, forgiving syntax that is consistent across all modules. Instantly visualize your results with SYSTAT's Quick graphs, produced automatically by most statistical procedures to provide immediate and intuitive feedback.

10.4.6 COMPLETELY AUTOMATE YOUR ANALYSIS

Speeding up data analyses with SYSTAT's flexible command language that provides complete coverage of menu-based functionality. Quickly run the same analysis on different data using token variables in command templates. Each time command file is run, a variable is selected. Create command files in no time.

Execute functions using the menus and dialog selections, while the command log helps in viewing the steps. Simply save the command log script to rerun the analysis. Track and report your statistical methodology to monitoring agencies using the command log. Create compelling reports by combining formatted statistical output with publication-quality graphs in SYSTAT's rich text output window then automation is done.

10.4.7 MORE GRAPHS

SYSTAT offers more graph types and options than any other desktop statistics package. Create insightful presentations with advanced chart types, such as maps, multiplots, and kernel densities. These are but a few of the many, many advance chart capabilities built into SYSTAT that really indicate the excellence that has been coded in this program. Speed up your analysis with SYSTAT's interactive graphic tools. Simply point-and-click to perfect your graph's appearance.

10.4.8 LESS EFFORT

With enough of difficult programming languages or elaborate interface designs, SYSTAT's intuitive Windows interface and flexible command language are designed to make research more efficient. Quickly locate advanced options through clear, comprehensive dialogs. Fly through analysis with interactive commands, and instantly visualize your results with SYSTAT's **Quick Graphs.** This program will support users as it automatically modifies processes to find the best results. The program automatically seeks a course of action that will optimize your entire system's performance.

10.4.9 OPTIMISATION USING SYSTAT

Optimization of heat pipe heat exchanger is done using systat software.

The program for generating the response surface is given below

PROGRAM:

```
EYE -6,-8,6

BEGIN

FACET XY

FPLOT Z=0.649+1.724*X+1.410*Y-0.736*X*X-0.496*Y*Y; CONTOUR,

SURFACE=XYCUT CUT=8, ZTICK=8, XPIP=5, YPIP=5, XLAB=", YLAB=",
ZLAB='',

XMIN=0, XMAX=2,

YMIN=0, YMAX=2

FACET

FPLOT Z=0.649+1.724*X+1.410*Y-0.736*X*X-0.496*Y*Y;,

SURFACE=XYCUT CUT=8, ZTICK=5, ZPIP=5,  XLAB='Load in kg', YLAB='
Mass flow rate in LPM.' ZLAB='HPHRR KW',

ZMIN=0.5, ZMAX=3,

XMIN=0, XMAX=2,

YMIN=0, YMAX=2

END
```

10.5 INTERACTIVE EFFECT OF LOAD AND MASS FLOW RATE ON HPHRR

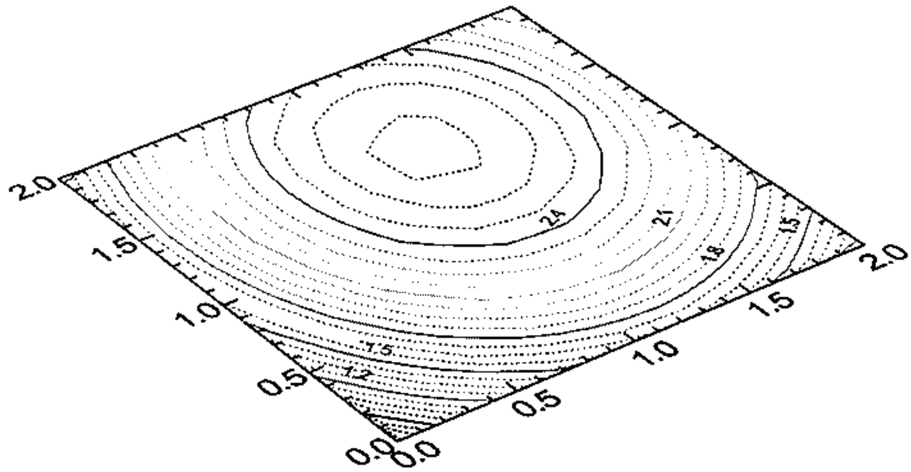

FIGURE 10.1 INTERACTIVE EFFECTS OF LOAD AND MASS FLOW RATE

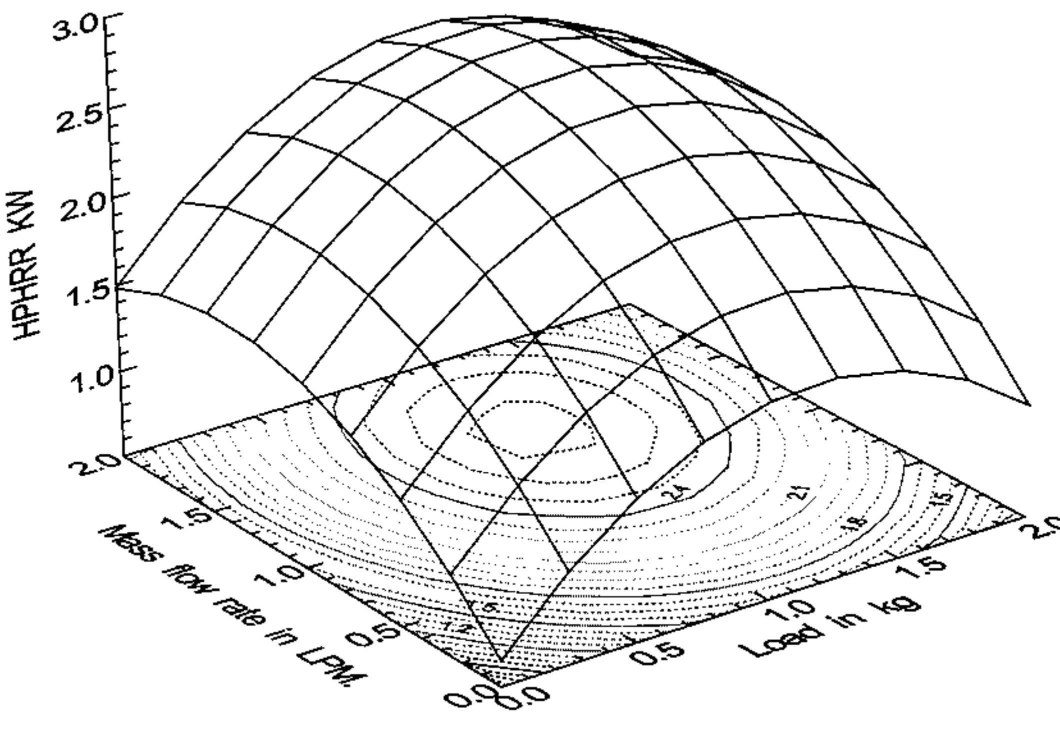

FIGURE10.2 INTERACTIVE GRAPH OF LOAD AND MASS FLOW RATE

The fig10.1 and fig 10.2 shows the interactive effect of load and mass flow rate on heat pipe heat recovery rate. From the contour surface, the HPHRR increases with inceases in load upto 6 kg but decreases with further increase in load similarly the HPHRR increases with increase in mass flow rate upto 1.5 lpm but decreases with further in mass flow rate. The heat recovery rate is maximum at the load is at its middle level(1) and mass flow rate at its middle level(1) the maximum heat recovery possible is 2.6 kW.

CHAPTER 11

ECONOMIC FEASIBILTY

The tests that were conducted proved this systems functioning efficiency. Following are the steps to study the feasibility of our project.

- Total cost of implementing this system is Rs 10,000/-.
- This system functions as an effective medium to recover heat from the diesel engine exhaust.
- The heat pipes can be used to recover heat effectively for other systems like refrigerators, air conditioning plants.
- The operating temperature of this specific heat pipes are 60°c to 105°c.
- The life of the pipe comes between 4 to 5 years.
- The heat transfer capacity depends upon the purity of the fluid used and the material of the pipe.
- Non corrosive elements are best suitable for this kind of applications.
- Vacuum should be maintained so that the heat transfer is effective .vacuuming could be a cost consuming process, but it is a must for the construction of this pipe.
- Aluminium, copper, stainless steel are best suitable one for pipe construction. stainless steel can be used for cases like corrosive liquids like water.
- Wick materials should be same as the pipe materials, because the wick and the pipe should not react at high temperature in presence of a fluid.

CHAPTER 12

CONCLUSIONS

Heat pipe is equipment used to transfer heat from one point to the other with least loss which helps in increasing the heat transfer efficiency. Once the waste heat is transferred, the waste heat can be used for other process which is secondary in nature. Though the processes are secondary in nature they show a notable increase in the efficiency of the overall system by using waste heat instead of fresh energy. Thus the application of heat pipes is to recover the waste heat and use it for improving the efficiency of the system. A copper – water heat pipe is fabricated for three different lengths and tested for heat transfer limitations. From the characteristic curves drawn, it is concluded that the copper water heat pipe can be used for higher operating temperatures. From the three pipes the best is selected for fabrication into a heat pipe heat exchanger. The heat pipe heat exchanger is used for recovering the waste heat from the engine exhaust. The experiments were conducted as per the design matrix using DOE. The mathematical model developed is useful to analyze the heat recovery rate of the heat pipe heat exchanger. The heat pipe heat exchanger is able to recover a maximum heat of 2.4 kW. The optimization of the heat pipe heat exchanger is done using SYSTAT soft ware. The interactive effect of load and mass flow rate on heat pipe heat recovery is analyzed and the optimum heat recovery is obtained at 6 kg load and for a mass flow rate of 1.5 liters per minute.

APPENDIX

PHOTO 1 HEAT PIPE HEAT EXCHANGER (IN THE EXHAUST LINE OF DIESEL ENGINE)

PHOTO 2 TESTING OF HEAT PIPE

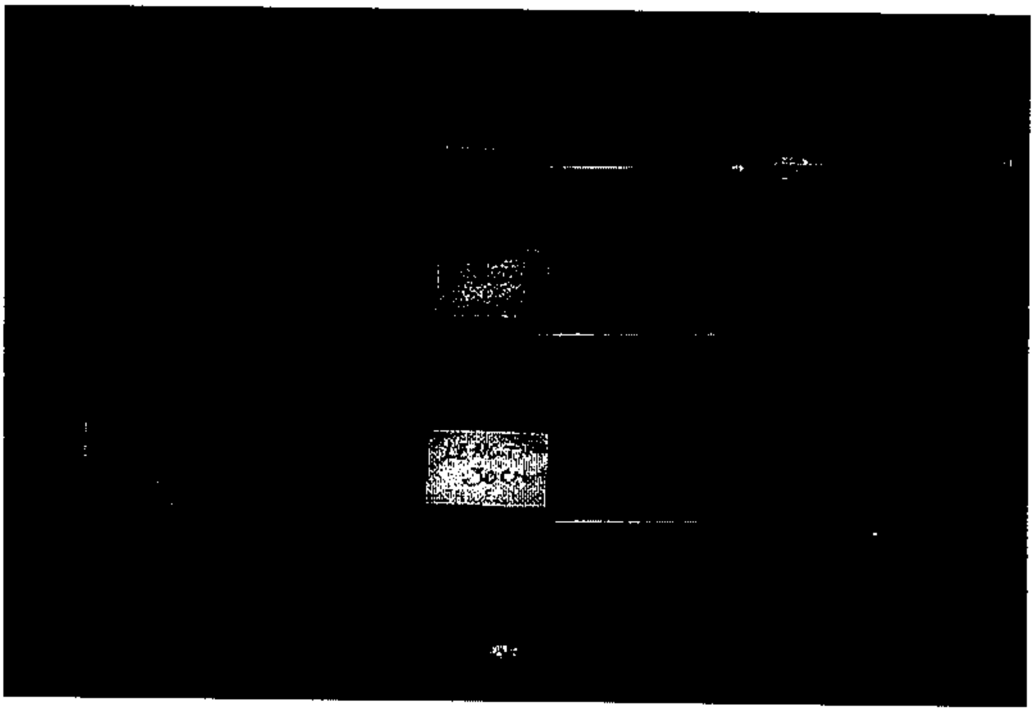

PHOTO 3 HEAT PIPES OF VARYING LENGTH AND PRESSURE GAUGE

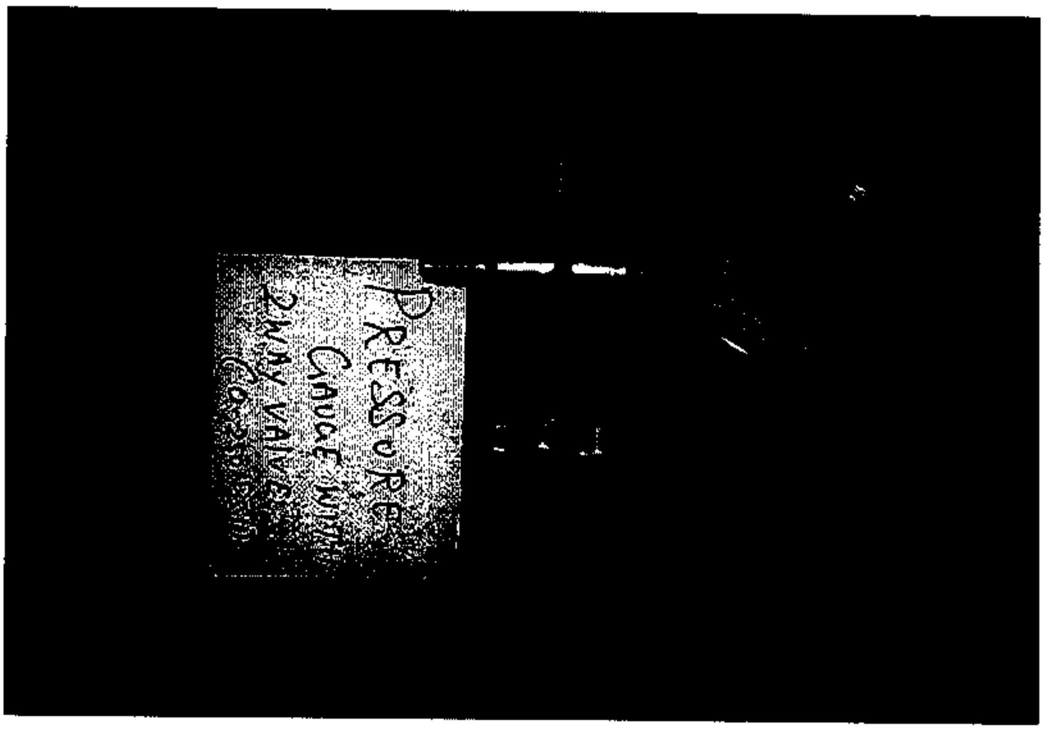

PHOTO 4 PRESSURE GAUGE (250PSI)

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