Investigation and Characterization of Heat Pipe using Enhanced Surfaces

Submitted By

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Submitted in partial fulfillment of the requirements

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(Thermal Engineering)

Submitted By

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May 2018

Declaration

This is to certify that

I. The report comprises my original work towards the degree of Master of Technology in Mechanical Engineering (Thermal Engineering) at Nirma University and has not been submitted elsewhere for a degree.

II. Due acknowledgement has been made in the text to all other material used.

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Undertaking for Originality of the Work

I, **Rashi Khandelwal**, Roll No.**16MMET21**, give undertaking that the Major Project entitled "**Investigation and Characterization of Heat Pipe using Enhanced Surfaces**" submitted by me, towards the partial fulfillment of the requirements for the degree of **Master of Technology in Mechanical Engineering (Thermal Engineering)** of Institute of Technology, Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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-Rashi Khandelwal

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Abstract

During the last two decades and more, the component density on integrated circuits has grown from about six thousand transistors on the microprocessor to over five million transistors on a similar-sized microprocessor. The increased power and component densities on these integrated circuits necessitated the development of innovative cooling methods. For the same, heat pipes are extensively used as heat transmission device because of the advantages like constructional simplicity, exceptional flexibility, accessibility to control and an ability to transport heat with small temperature drop without requiring any external pumping work. The miniature heat pipes (MHPs) appear promising for use in microelectronics cooling.

In the present study, an experimental study is carried out to understand the heat transfer performance of Miniature Heat Pipes (length = 200mm and diameter = 8mm) which can be applied for cooling solution of electronics equipment such as the computer CPU, etc. The screen meshed copper heat pipe is studied for various orientations and various performance parameters like effective thermal resistance, effective thermal conductivity, heat transfer coefficients and efficiency. Further the calculation of various parameters of mesh and heat transfer limitations of heat pipe are evaluated theoretically.

The effect of heat pipe orientation on the thermal performance was experimentally determined. It was observed that the orientation of heat pipe at 45°(gravity assisted-condenser oriented upwards) performed most efficiently and the average improvement was 25.19 % with respect to the horizontal position of heat pipe.

Key words: Miniature Heat pipe, Heat transfer limitations, Screen meshed copper heat pipe, effective thermal resistance, effective thermal conductance, efficiency.

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Nomenclature

L	Latent Heat, J/Kg
M	Figure of Merit / Merit Number / Liquid Transport Factor, W/m^2
P	Pressure, KPa/ Porosity
ΔP	Pressure loss
D	Diameter, mm
A	Area,m^2
R	Radius, mm
Q	Heat Load/ Limitation, W
L	Length, mm
R	Gas constant, J/(mol K)
T	Temperature,$^\circ$ C
K	Thermal conductivity, W/(m K)
t	Thickness,mm
N	Wick/Screen mesh size, inch^{-1}
K	Permeability
G	Gravitational constant, kg m/s^2
R	Thermal resistance, K/W
V	Vapour velocity, m/s
Subscripts	
l	Liquid
v	Vapour, Vapour Core
c	Capillary, Condenser
e	Entrainment, Evaporator
vis	Viscous
eff	Effective
h,w	Hydraulic parameter of wick
th	Thermal
s	Sonic
b	Boiling
i	Inner
o	Outer
W	Wick, Wire
in	Input
out	Output
p	at constant pressure

Abbreviations

TCS	Thermal Control System
CFD	Computational Fluid Dynamics
CAD	Computer Aided Drawing.
CPU	Central Processing Unit
MHP	Miniature heat pipe
LHP	Loop heat pipe
PHP	Pulsating Heat Pipe
FHP	Flexible Heat Pipe
FEA	Finite Element Analysis

Chapter 1

Introduction

1.1 Thermal Control of Electronics

Electronic equipment has made its way into nearly every aspect of modern life, from toys and appliances to high-power computers. The major factor in the overall reliability of the system is the consistency of the electronics of a system. Electronic components works when electric current is passed through , and they become potential sites for unnecessary heating, since the current flow throughout a resistance is accompanied by heat generation. Continued miniaturization of electronic systems has resulted in a remarkable raise in the amount of heat generated per unit volume. These high rates of heat generation result in high operating temperatures for electronic equipment, which endanger its safety and reliability and hence proper design and control is required. The failure rate of electronic equipment increases exponentially with temperature. Also, the elevated thermal stresses in the solder joints of electronic components mounted on circuit boards resulting from temperature variations are chief causes of failure. Therefore, advancement in cooling technologies is required. As a result thermal management is becoming important and increasingly serious to the electronics industry. The major challenge to the thermal engineers is to maintain acceptable junction temperature by dissipating the heat from the incorporated circuit chips.

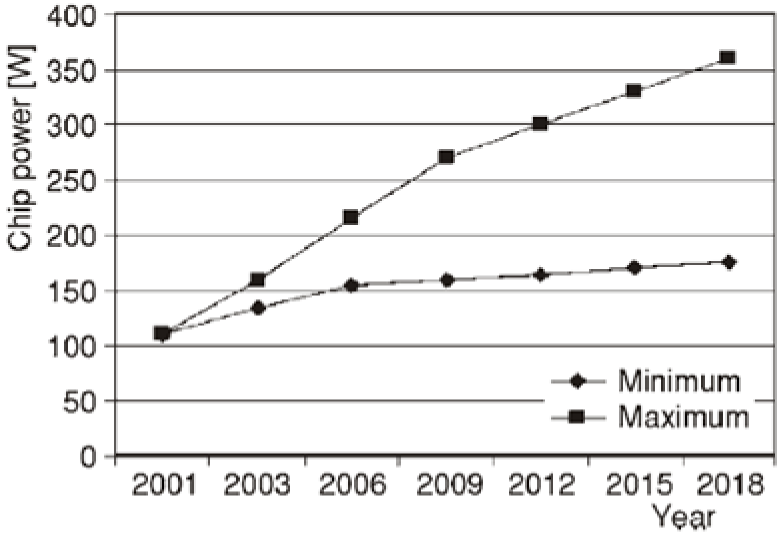

Figure 1.1: High performance chip power trend [1]

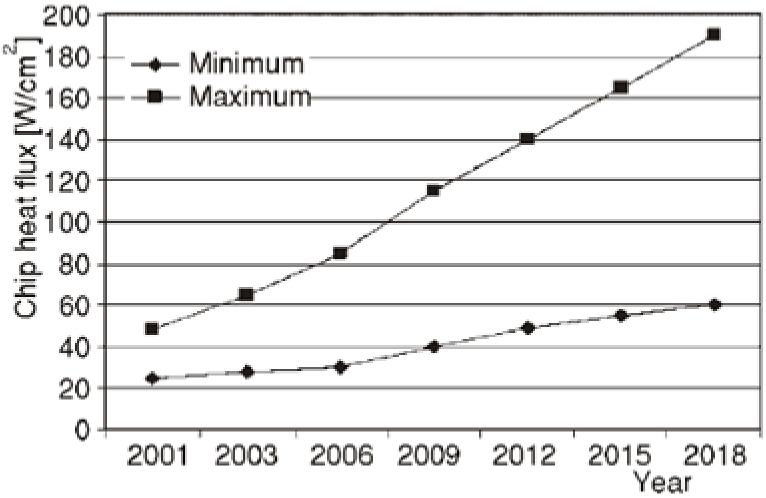

Figure 1.2: High performance chip heat flux trends [1]

The electronics cooling is viewed in three levels [1], which are non separable. First, the maintenance of chip temperature at comparatively low level despite of high local heat density. Second, this heat flux must be handled at system or component level. Finally, the thermal management of the computer machine room, office space, or telecommunication enclosure. The thermal design of the system is influenced by the key drivers like chip size, power dissipation, junction temperature and ambient air temperature. The semi conductor industries are taking great amount of effort over the years to reduce the size of the devices. With the increase in power dissipation and reduction in the size, the growth in power density is expected to increase further over the next decade as shown in figs. 1 and 2. The growing power density indicates the thermal management solutions play an important role in determining the future semiconductor device technology.

1.1.1 Thermal Problems in electronics

The documentation of heat load in process equipment by a thermal management consortium projects the increasing trend of power dissipation. Advanced thermal architecture is required to meet this stringent thermal requirement. The high chip temperature results in thermal failures such as mechanical stresses, thermal de-bonding and thermal fracture. Lasance [7] mentioned three typical reasons for the ever increasing importance of thermal management. The reasons are: at the component level, designers try to minimize package dimensions while increasing power density, which makes the problem of minimizing the thermal resistance from junction to case, a crucial part of the package density, secondly, the electronic industries thermal design tends to be an afterthought of the design process only if the prototype raises any thermal issues, and thirdly, the limit of pushing the use of air cooling with heat sink and fan is expected to be reached in the coming years. Therefore thermal management is a key enabling technology in the expansion of advance electronics. It is a indispensable part of any competitive power density environment. Though the new tool and technologies are employed for cooling, there is no remarkable change in the constraints and design requirements. Thermal management cannot be the driving force behind new designs. It must be disposed with other requirements and constraints. The main constraint for any thermal management is the cost. Therefore the cooling technology must be cost effective and keep pace with the reduction in overall package and system cost per function. The cost of cooling is also recognized as a factor playing important role in maintaining competitiveness.

1.2 Heat Pipe- An overview

A heat pipe is a heat transfer device that can transport huge amount of heat with a very small temperature difference between the hot ends and cold end. Alternatively, it is a device that rapidly transfers heat from one point to another. Due to their astonishing heat transfer capacity and near about no heat loss, these are often mentioned as "superconductors" of heat.

Basically, it is composed of a sealed metallic container with internal surfaces have a capillary wicking material. A heat pipe is alike a thermo-syphon. It varies from a thermo-syphon by virtue of its potentiality to carry heat against gravity by an evaporation-condensation cycle with the aid of porous capillaries that make the wick. The wick provides the capillary driving force to return the condensate to the evaporator. The heart of the product is its wick structure as it determines the performance of the heat pipe. Depending on the application for which the heat pipe is being utilized, different types of wicks are used.

1.3 Methods for Characterizing Heat Pipe

There are 3 methods for characterization of heat pipe:

1.3.1 Theoretical modelling and analysis

One of the way to characterize heat pipe performance is by mathematical model. Since even the simplest heat pipe configurations which presents two dimensional axis-symmetric geometries includes two-phase constitutive relationships, mathematical modelling is quite complex. For a heat pipe, there are two kinds of mathematical models: steady state model and transient model.

1.3.2 Simulation

Simulation of two-phase flow, especially liquid-vapour flow inside a horizontal pipe using CFD is a very strenuous task. For simulation of the heat pipe, various two phase models are available. User defined function can be written to simulate the evaporation and condensation inside a heat pipe simultaneously.

1.3.3 Experimentation

To determine performance characteristics such as effective thermal conductivity, effective thermal conductance, efficiency and heat transport limitations of the heat pipe various experiments are carried out. There are different testing techniques to govern the steady state and transient characteristics of the heat pipe.

1.4 Problem motivation

Heat pipe are widely used in electronics but then also it is required to enhance their performance by improving efficiency because heating problems are observed in electronics (computers, laptops etc.). High heat is generated as the load on the processor of the system is increasing due to high speed and complexities. Hence it is required to dissipate heat as early as possible by improving the performance of heat pipe. The present study is also based on the very same problem.

1.5 Objectives of present study

The literature review conducted in the area of Heat Pipes reveals that there is a requirement to conduct further work on miniature heat pipe to fulfill the need of high heat dissipation with surface enhancement.

This study mainly aims at:

1. Design an experiment for miniature copper screen meshed heat pipe satisfying all five heat transport limitations.

2. Develop a copper screen meshed heat pipe based on concluded design and evaluate its thermal performance in terms of effective thermal conductivity and thermal conductance and efficiency.

3. Compare the thermal performance of miniature copper screen meshed heat pipe at different power inputs, angle of orientation and mesh size.

4. Measure various parameters of heat pipe like mesh size, wire diameter, surface roughness etc.

1.6 Thesis outline

The thesis outlines of each chapter are specified as follows:

Chapter 1 expresses the electronics thermal control system, an overview on heat pipe, various methods for characterizing the heat pipe, problem motivation, objectives of the study.

Chapter 2 reviews the historical development of a heat pipe along with the principles of working components, the types of heat pipe, major heat transport limitations of heat pipe and advantages, disadvantages and applications of heat pipe.

Chapter 3 reviews the experimental work carried out to investigate heat pipe.

Chapter 4 reviews the results obtained from the experimental work carried out and discussion based on the results.

Chapter 5 describes the conclusion drawn from the present work and the scope of future work possible in this context.

Chapter 2

Literature Survey

This chapter reviews the historical development of a heat pipe. Also the principles of working components, the types of heat pipe, major heat transport limitations of heat pipe and advantages, disadvantages and applications of heat pipe are discussed. This chapter builds the foundation for the dissertation work.

2.1 Historical development

Heat pipes have been invented around since the 1800s when Jacob Perkins and his company developed the Perkins tube which was used to transfer heat from a furnace to a boiler. It was invented by Perkins family was wickless and gravity assisted which design was very closet to present heat pipe patented by Jacob Perkins.

R. S. Gaugler [8] filed the first US heat pipe for application to the cooling of interior of an ice box. He introduced one of the key components of a modern heat pipe, known as wick structure, allowing the heat pipe to work against gravity.

Grover[9] et al. At Los Almos National Laboratory in New Maxico published the work of research on the heat pipe. He showed a greater capacity that this device has a higher thermal conductivity than any known metal. From this research, he coined the term heat pipe. Grover, Cotter and Erickson publish the first technical paper on the heat pipe in 1964. In 1965, T. P. Cotter publishes the first heat pipe analysis (theory of heat pipes). Cotter [10] proposed the concept of micro heat pipe, which essentially ia a wickless heat pipe for the uniform temperature distribution in electronic chips.

Amir faghri [11] defined that heat pipe was an passive device for radiating heat at a larger rate over a distance with small temperature drops between two temperature limits. Heat pipe comprises of three sections namely evaporator, adiabatic and condenser. The heat is supplied to the heat pipe in the evaporator section which converts the working fluid into vapour and returned to the condenser, due to capillary action of the wick structure. Yu-wei chang [12] utilised the heat pipe for cooling the electronic components and concluded that the evaporation resistance and condensation both increases with increase in heat input and decreases with filling ratio.

Seok Hwan moon[13] implemented the concept of miniature heat pipe with wick material of woven to increase the cooling effect of notebook PC and showed that miniature heat pipe MHP cooling modules with wicks satisfies a demand condition of 0 to 100°C.

Khalid Joudi et al [14] compared the performance of gravity assisted heat pipe with modified heat pipe with a separator in the adiabatic section. The results evidenced that modified heat pipe with separator is more efficient than gravity assisted heat pipe.

Shinzo Shibayama and Shinichi Morooka [15] analysed both experimental and theoretical about the various limits such as capillary limit, maximum heat transfer limit of wick, friction loss and capillary properties.

A. K.Mozumder et al [16] made an attempt to design, fabricate and test a miniature heat pipe with 5 mm diameter and 150 mm length with a thermal capacity of 10 W. Experiments were conducted with and without working fluid for different thermal loads to assess the performance of heat pipe. Finally the optimum liquid fill ratio is identified in terms of lower temperature difference, thermal resistance and higher heat transfer co-efficient.

Faghri et al [17] numerically analysed the transient and steady state performance of heat pipes with multiple heat sources and sinks. They concluded that the steady state of the heat pipe significantly changes with a change in the emissivity of the heat pipe wall and subsequently increases the power input in the evaporator section.

Sun et al [18] the results implicated that a higher value of the capillary heat transport limit can be achieved when the heater placed symmetrically at the centre of the evaporator section as compared to the one side of the evaporator section.

Patrik Nemec et al [19] made a detailed study about the working position of the heat pipe in both horizontal and vertical direction .They concluded that heat pipe can able to operate at both positions.

Manikandan et al [20] analysed the effect of container diameter of heat pipe using Response Surface Methodology method to determine the optimal diameter. From that analysis the optimum diameter of heat pipe is 20 mm based on the thermal efficiency and thermal resistance.

Senthil kumar et al [21] analysed the heat pipe used in the energy conservation and waste heat recovery system. In their work, the heat pipe is fabricated with two layers of mesh size 80 /square inch and analysed the effect of using nanofluids in the heat pipe.

K.N.Shukla et al [22] used four layered 100 mesh size copper screen to measure the thermal performance of cylindrical heat pipe using nanofluids and noticed that it is more improvement in the heat transfer coefficient.

Ghanbarpour et al [23] used two layers of screen mesh wick of 150 mesh size to study the performance of heat pipe using silver nanofluids as a working fluid. They result showed that thermal conductivity is better at 60 angle of inclination.

Tauofik brahim et al [24] used various screen mesh number in the heat pipe which is used in the solar collector and confirmed that heat pipe fabricated with two layers of screen mesh wick of mesh number 100 have increased the solar collector efficiency.

Bhooomipagu et al [25] used copper screen mesh of 100 holes/square inch to generate capillary pressure in the square copper heat pipe. They compared the results thermal efficiency is better at 75% of filing ratio when water as a working fluid and 100% of filling ratio when Cuo as a working fluids.

Senthil Kumar et al [26] used same two layers of stainless screen mesh of different mesh number of 60 square /inch to study the performance of heat pipe. The results showed1 that thermal efficiency was better at 45 for water and 60 for nanofluid.

Loh et al. [27] compared the thermal performance of cylindrical heat pipes having different wick structures at various tilt angles. Experimental results suggested that the sintered wicks holds good for anti-gravity orientations and grooved heat pipe for gravity assisted orientations.

Yousefi et al. [28] studied the influence of inclination angle of a heat pipe used for CPU cooling using nanofluids. The results showed that inclination angle is important parameter influencing CPU temperature.

Tao et al. [29] analyzed the working of a flattened heat pipes having diverse thicknesses of 3.5 mm, 3 mm, 2.5 mm, and 2 mm. The results showed that the decrease in thickness of flattened heat pipe led to increase in thermal resistance.

Jiang et al.[30] used a flattened heat pipe fabricated from a cylindrical heat pipe having a composite wick of grooved sintered wick for heat transfer study. The test results were compared with a grooved wick and sintered wick flattened heat pipe. Results showed that the thermal resistance of heat pipe with composite wick was in between grooved wick and sintered wick flattened heat pipes.

Li et al. [31] studied the influence of flattened thickness on the thermal performance of a flattened heat pipe having sintered wick using experiments and mathematical model. The results showed a decreasing trend in heat transfer when thickness of the flattened heat pipe was reduced.

Lin and Wong [32] experimentally investigated the heat transfer phenomenon of a grooved and sintered flattened heat pipes using water as the operating fluid. A reduction in heat transfer was observed in flattened heat pipe which was attributed to liquid clogging at condenser region and inter facial shear between vapour and liquid in sintered and grooved heat pipes respectively.

Li et al. [33] studied the heat transfer phenomenon in a thin flattened heat pipe having composite wick structures and examined the limits of the heat pipe. The maximum heat transfer limit was found to be less than 14W at optimum filling ratios.

2.2 Background

The heat transfer plays a very important role in present day innovations. All electronic components release huge unusable heat which must be extracted effectively within time. Hence, research is going on to discover more effective methods for moving heat from one place to another. Heat pipes are gadgets that can exchange extensive measure of heat with little temperature difference between evaporator i.e. the heat source and condenser i.e. heat sink. This property can be seen better when a heat pipe is contrasted and aluminum or a copper bar, as showed in the case underneath. [34]

Expect that it is required to exchange Q = 20W of heat over a length of L = 0.5m , = 1.27 cm in breadth. As appeared in Fig 2.1, utilizing Fourier's law the temperature difference required to exchange this heat will be as follows:

Solid aluminum rod = 460°C

Solid copper rod = 206°C

Simple copper-water heat pipe with a screen work wick = 6°C.

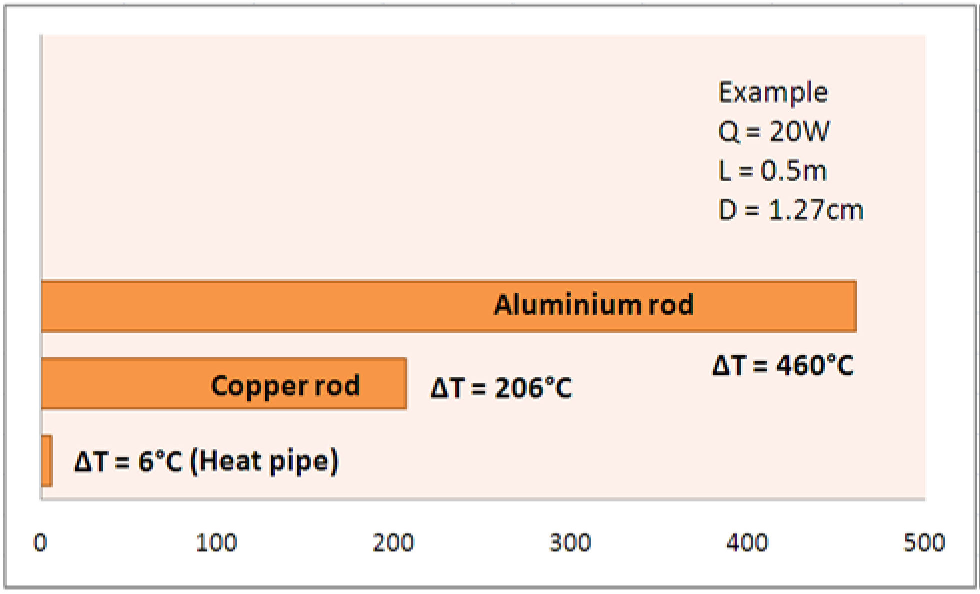

Figure 2.1: Comparison of heat pipe and solid conductors

2.3 Thermodynamics of heat pipe

Consider a simple heat pipe (Fig. 2.2) along with an isothermal situation. The fluid in the wick and the vapour in the vapour space are at immersion.

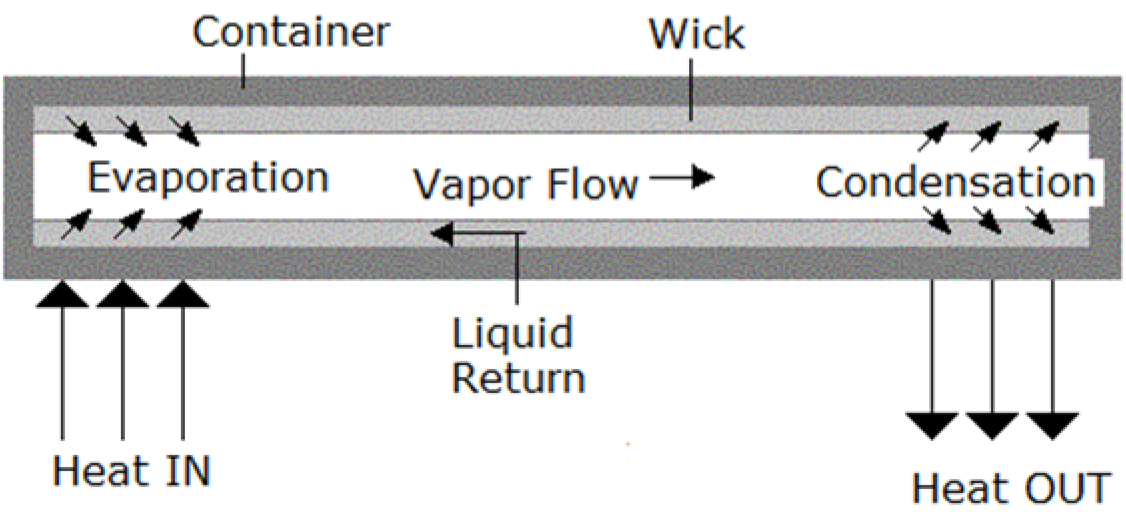

Figure 2.2: Thermodynamics of Heat Pipe

Thermodynamic cycle of heat pipe is appeared in Figure 2.3.

Points of interest of procedures included are as under:

a) 1-2: Heat connected to evaporator through outer sources, vaporizes working liquid to a saturated state (2') or superheated state (2) of vapour.

b) 2-3: Vapour pressure drives vapour through adiabatic area to condenser.

c) 3-4: Vapour condensed, discharging heat to a heat sink.

d) 4-1: Capillary pressure made by menisci in wick pumps dense liquid into evaporator segment.

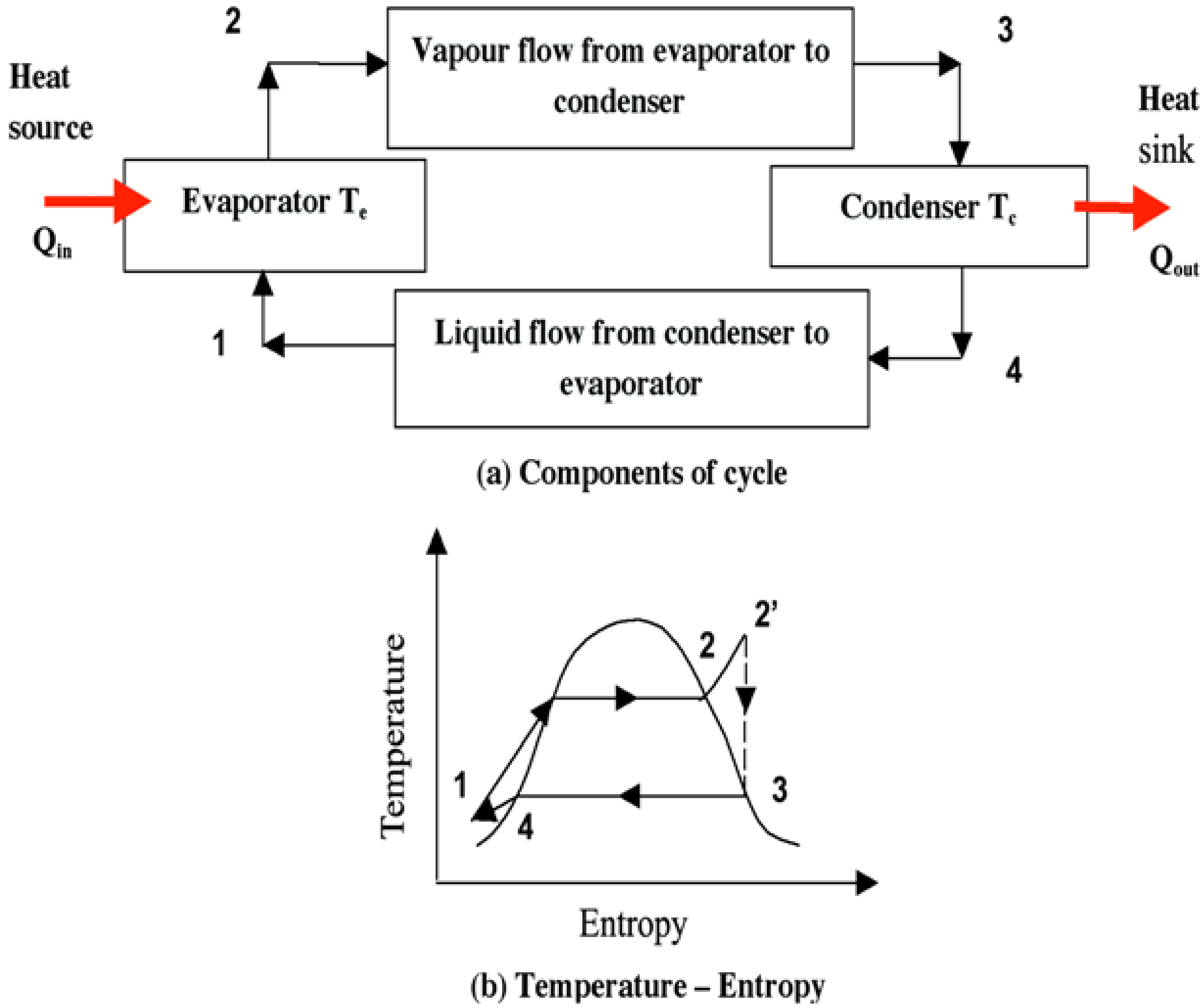

Figure 2.3: Thermodynamics cycle of heat pipe

2.4 Heat Pipe Construction

The length of the heat pipe is separated into three areas as appeared in Figure 2.4.

a) Evaporator area - The region where the outer heat source is connected with the heat pipe.

b) Adiabatic (transport) segment - The locale where the heat pipe is remotely insulated and no heat exchange to or from the heat pipe

c) Condenser segment - The area from where the heat is discharged to heat sink.

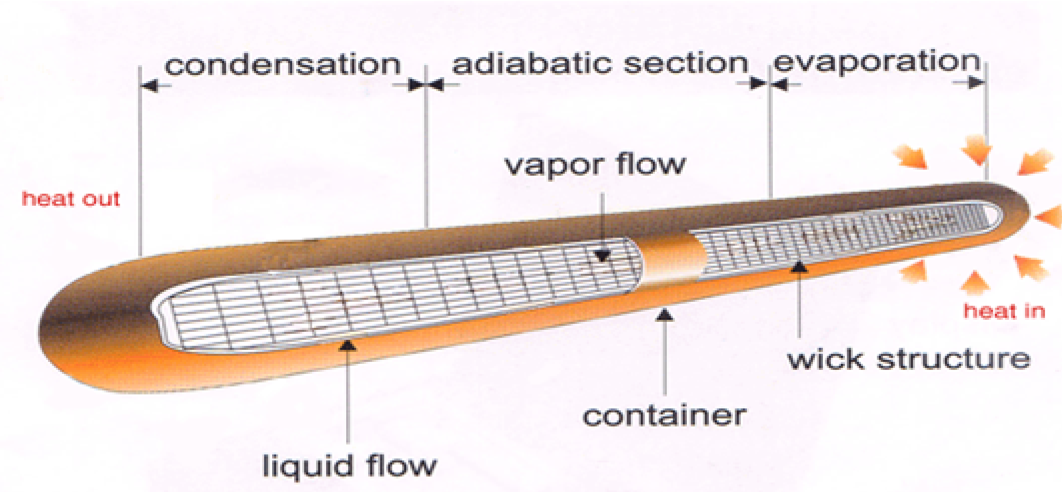

Figure 2.4: Heat pipe construction

From figure 2.4, it can be observed that the heat pipe has three primary areas:

1. Container
2. Wick/ capillary structure
3. Working fluid

2.4.1 Container

The function of the container is to seperate the working fluid from the outside condition. It must be sealed container which creates vapour pressure difference and causes fluid to move inside the pipe.

Determination of the compartment material depends upon many constituents.[2] These are as per the following:

1. Compatibility (both with working liquid and outside condition)

2. Strength-to-weight proportion
3. Thermal conductivity
4. Ease of fabrication, including welding, machinability, and ductility
5. Porosity
6. Wettability

Copper, aluminium and stainless steel are most commonly used. Copper is used mainly in hardware industry while aluminium because of its high quality to weight proportion is a great selection for space applications. The material ought to be non-permeable to keep the dissemination of vapour. A high heat conductivity guarantees least temperature drop between the heat source and the wick.

2.4.2 Wick or Capillary Structure

The prime inspiration driving the wick is to make slim strain to transport the working fluid from the condenser to the evaporator. It ought to in like manner have the ability to pass on the liquid around the evaporator portion to any zone where heat is most likely going to be gotten by the heat pipe. Routinely these two limits require wicks of different structures. The assurance of the wick for a heat pipe depends upon numerous components, a couple of which are immovably associated with the properties of the working fluid.

The most extraordinary thin head made by wick increments with reduce in pore measure. The wick penetrability increases with extending pore estimate. Another component of the wick, which must be enhanced, is its thickness. The heat transport limit of the heat pipe is raised by extending the wick thickness. The general heat protection at the evaporator moreover depends upon the conductivity of the working fluid in the wick. Other crucial properties of the wick are comparability with the working fluid and wettability.[2] The most generally perceived sorts of wicks are screen work, sintered work and notched compose.

2.4.3 Working Fluid

A first thought in the identification of a suitable working liquid is the working vapor temperature range. Inside the estimated temperature band, several possible working liquids may exist, and an assortment of qualities must be inspected with a specific end goal to decide the most worthy of these liquids for the application considered. The prime necessities are:

1. Compatibility with wick and wall materials
2. Good thermal stability
3. Wettability of wick and wall materials
4. Vapour pressure not too high or low over the operating temperature range
5. High latent heat
6. High thermal conductivity
7. Low liquid and vapour viscosity
8. High surface tension
9. 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 such as, 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 vapour pressure over the operating temperature range must be sufficiently great to avoid high vapour 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 vapour and liquid viscosity.[2]

The highest performance from a heat pipe is obtained by utilizing a working fluid that has a high surface tension(σ), a high latent heat (L), and a low liquid viscosity (μ_l). These fluid properties are contained in the parameter M, Figure of Merit or the Liquid Transport Factor. The working fluid's ability to transport heat can be judged by liquid transport factor or figure of Merit, M. Higher will be the M, better will be the heat transport capability.

$$M = \frac{\sigma_l \ \rho_l \ \mathrm{L}}{\mu_l} \tag{2.1}$$

Heat Pipe Working Fluid	**Operating Temperature Range (C)**
Low Temperature or Cryogenic Heat Pipe Working Fluids	
Carbon dioxide	-50 to 30
Helium	-271 to -269
Hydrogen	-260 to -230
Methane	-180 to -100
Neon	-240 to -230
Nitrogen	-200 to -160
Oxygen	-210 to -130
Mid-Range Heat Pipe Working Fluids	
Acetone	-48 to 125
Ammonia	-75 to 125
Ethane	-150 to 25
Methanol	-75 to 120
Methylamine	-90 to 125
Pentane	-125 to 125
Propylene	-150 to 60
Water	1 to 325
High Temperature (>300C) Heat Pipe Fluids	
Cesium	350 to 925
NaK	425 to 825
Potassium	400 to 1,025
Sodium	500 to 1,225
Lithium	925 to 1,825
Silver	1,625 to 2,025

Table 2.1: Typical heat pipe working fluids and operating temperature range [5]

Working fluid	Compatible Container Material	Incompatible Container Material
Acetone	Aluminium, Brass, Copper, Silica, Stainless Steel	-
Ammonia	Aluminium, Iron, Nickel, Stainless Steel	Copper
Cesium	Niobium, Titanium	-
Dowtherm	Copper, Silica, Stainless Steel	-
Freon-11	Aluminium	-
Heptane	Aluminium	-
Lead	Tantalum, Tungsten	Inconel, Nickel, Niobium, Stainless steel, Titanium
Lithium	Niobium, Tantalum, Tungsten	Inconel, Nickel,Stainless steel, Titanium
Mercury	Stainless steel	Iron, Nickel, Niobium, Tantalum, Titanium
Methanol	Brass, Copper, Iron, Silica, Stainless steel	-
Silver	Tantalum	Inconel, Nickel, Niobium, Stainless steel, Titanium
Sodium	Inconel, Nickel, Niobium, Stainless steel	Titanium
Water	Copper, Nickel, Silica, Stainless Steel, Titanium	Aluminium, Inconel

Table 2.2: Compatibility data[6]

2.5 Types of Heat Pipe

2.5.1 Heat pipe classification based on types of wick

1. Grooved Heat Pipes: Grooved Heat Pipes are basically utilized for space applications. The benefits of these gadgets have been called attention to by Hoa, Demolder and Alexandre (2003).They state: ”A large portion of heat pipes for space applications have pivotal depressions and are made of extruded aluminium 6063. The basic working liquid is smelling salts as its operational temperature is appropriate to space applications (- 40 to 80°C). Pivotally scored heat pipes offer moderately basic modern creation and more prominent dependability than other wick outlines, for example, course heat pipes.”

2. Mesh Wick Heat Pipes: Screen meshed heat pipes are one of the more seasoned composes and have been in the commercial centre since the mid 1960’s when heat pipes

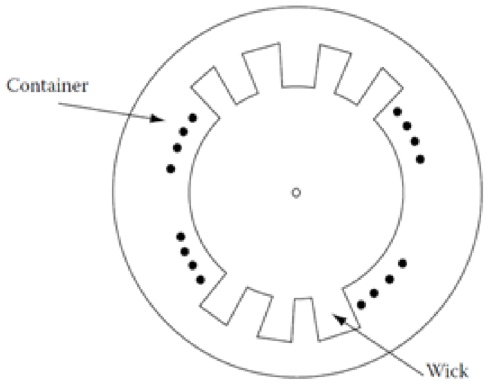

Figure 2.5: Axially Grooved Wick [2]

where specified by Cotter, Grover and Erickson (1964). They can be utilized as a part of different applications however do not have a particular market. Screen work wick heat pipes use solitary or different layers of woven wire material inside the heat pipe holder as the wick structure giving fine powers to restore the working liquid to the vanishing segment without gravitational help. For all the work exhibited the most widely recognized, and the one with the most astounding heat exchange capacities inside the low temperature district, working liquid is utilized, which is water.

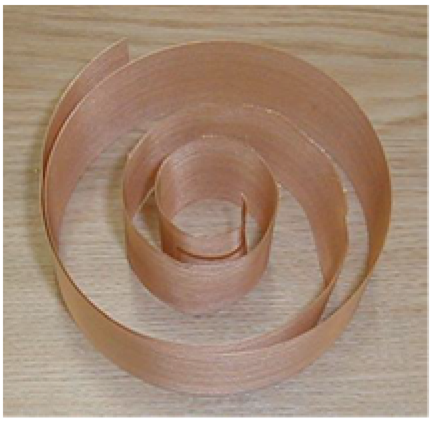

Figure 2.6: Screen Mesh as used for wick inside Heat Pipes [3]

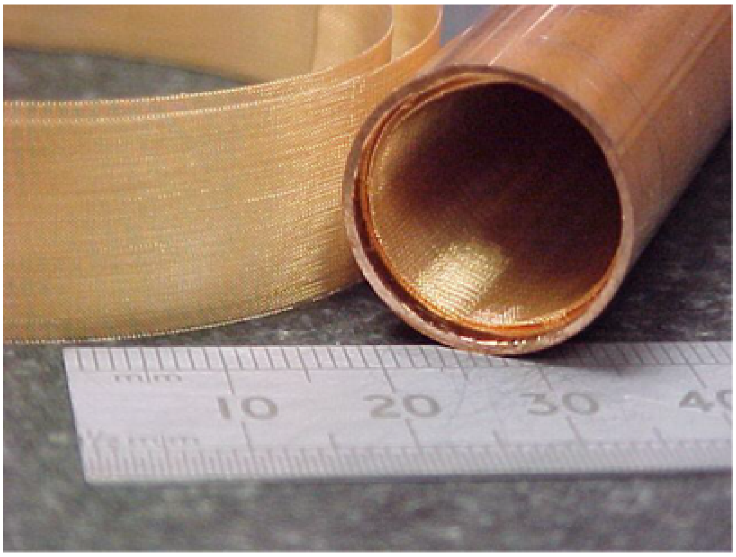

Figure 2.7: Picture showing internal construction of a screen mesh heat pipe [3]

3. Sintered Heat Pipes:

Sintered wick is a metal structure with a few voids in them. The vast majority of these wicks are created by compacting metal powders together and rising the temperature to directly underneath the powder particles dissolving temperature for the powders to get delicate, misshape at their contact point by the neighbouring particles lastly sinter together and to the heat pipe inward divider. The way toward sintering influences the permeable wick to structure. Notwithstanding high fine power, sintered heat pipes can expel more heat from the hot source per unit contact surface zone between the pipe and the source because of enhanced vanishing heat exchange.

Sintered heat pipes have the most elevated extent among all heat channels fabricated. They can be found in a wide range of electronic cooling applications including portable PCs, PCs and numerous more.[3]

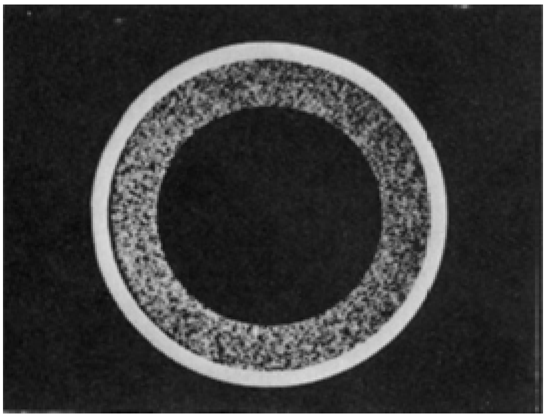

Figure 2.8: Sintered wick cross section (Copper)[4]

2.5.2 Heat pipe classification based on their conductance

1. Fixed conductance

The settled conductance heat pipe is a gadget of high heat conductance with no settled working temperature. Its temperature rises or falls as indicated by varieties in the heat source or heat sink.

2. Variable conductance

In many heat pipe applications a particular working temperature go is wanted along the certain bit of the pipe despite the fact that source and sink conditions are evolving. In those cases it winds up plainly important to effectively or inactively control the heat pipe with the goal that it maintains the wanted working temperature run. Temperature control is acquired by fluctuating one or a few of the conductance that make up the heat pipe's general heat conductance.

2.5.3 Advanced heat pipes

1. Loop heat pipe (LHP)

The Loop Heat Pipe comprises of a slim pump (or evaporator), a compensation chamber (or repository), a condenser, and fluid and vapour lines. The wicks are only exhibit in the evaporator and remuneration chamber. The high hairlike power is created in the evaporator because of essential wick structure. The pay chamber is a critical segment in the LHP and is frequently a basic part of the evaporator. The motivation behind the remuneration chamber is to oblige abundance fluid in an LHP amid ordinary operation.

An optional wick (normally made of bigger pores) physically interfaces the evaporator to the remuneration chamber to supply the essential wick with fluid, especially when the pay chamber is underneath the evaporator, or when the LHP is working in micro gravity conditions. The movement of vapour and fluid stream in the essential wick continues primarily in a spiral course. The evaporator meniscus is re positioned down toward the divider being heated. Both the fluid and vapour lines are made of little distance across tubing without any wicks. LHPs can be made adaptable and bendable. LHPs give heat evacuation over long separations without affect ability to gravity.A few variables make the LHP an alluring alternative for rocket cooling over conventional heat pipes. Since the wick structure is just in the evaporator, whatever is left of the compartment wall scan be smooth, which lessens weight drops in the vapour and fluid streams. The pressure drops all through the framework are likewise decreased on the grounds that the vapour and fluid stream are co current,as contradicted to the counter-current stream in ordinary heat channels. For these reasons,the LHP is a more powerful heat transport, and the heat source and sink can be isolated by a longer remove than with regular heat pipes.[35]

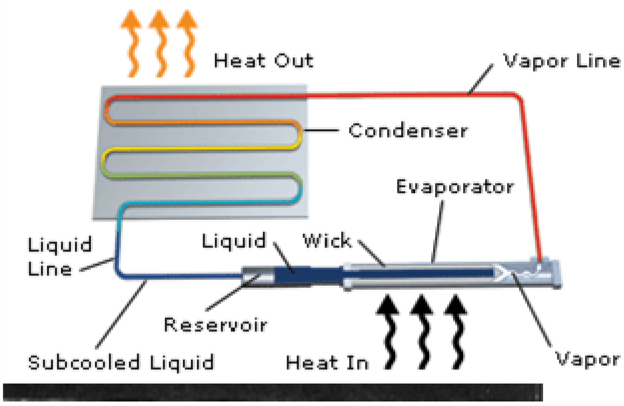

Figure 2.9: Loop heat pipe

2. Pulsating Heat Pipe (PHP)

The throbbing heat pipe (PHP) is produced using a long slender tube bowed into many turns, with the evaporator and condenser segments situated at these turns.

A PHP is generally in part accused of a working liquid, with a charge proportion between 40% and 60%. Since the width of a PHP is little (under 5mm), vapour attachments and fluid slugs are shaped because of narrow activity. Heat input either causes dissipation or boiling, which builds the weight of the vapour connect to the heating segment. All the while, the weight in the cooling segment diminishes because of buildup. This weight distinction pushes the fluid slug and vapour connect to the cooling segment. The fluid slug and vapour connect to the cooling area are then pushed into the following heating section,which will push the fluid slug and vapour plug back to the cooling segment. This procedure empowers the self-energized oscillatory movement of fluid slugs and vapour plugs. Heat is transported from the heating segment to the cooling area through the throb of the working fluid in the hub heading of the tube.

The extraordinary component of PHPs, contrasted with conventional heat pipes, is that there is no wick structure restoring the condensate to the heating section.There is in this way no counter current stream between the fluid and vapor. The entrainment limit in the traditional heat pipe does not have any impact on the limit of heat transport by a PHP. With this basic structure, the PHP weighs not as much as a traditional heat pipe, making it a perfect possibility for space applications. Since the measurement of the PHP is very small, surface strain assumes a more prominent part in the flow of the PHP than gravitational force does, empowering effective operation in a micro gravity situation. Different uses of PHPs incorporate heat control of electrical and electronic gadgets and segments, also as thyristors, diodes and fired resistors.[35]

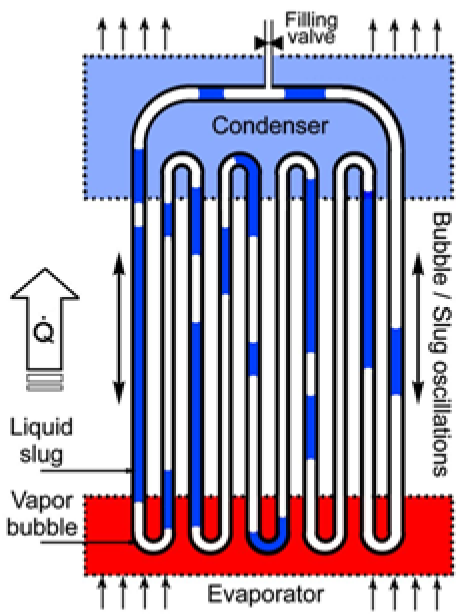

Figure 2.10: Pulsating heat pipe

3. Flexible Heat Pipe (FHP)

For enhanced aviation heat control with a requirement for flexibility of development, optical arrangement, least weight and most extreme unwavering quality, adaptable heat channels are a propelled heat pipe innovation that gives a perfect arrangement.

Figure 2.10 demonstrates a group of adaptable heat channels. The adiabatic section is produced using adaptable hose. This permits flexibility when mounting the heat pipe to the gadget being cooled and the heat sink. Moreover, the adaptable area can accommodate relative movement between the heat source and the sink. These heat channels were created for air ship utilize. The evaporator segment mounts to electronics on an actuator and the condenser connects to the flying machine structure. The actuator moves while the condenser stays stationary.[4]

Flexible heat pipes are attractive in applications where the gathering disallows incorporation of an inflexible heat pipe or where adaptability is expected to oblige vibration or temperature cycling. Adaptability is additionally required to allow in-circle sending, and introduction or scanning of indicator framework.

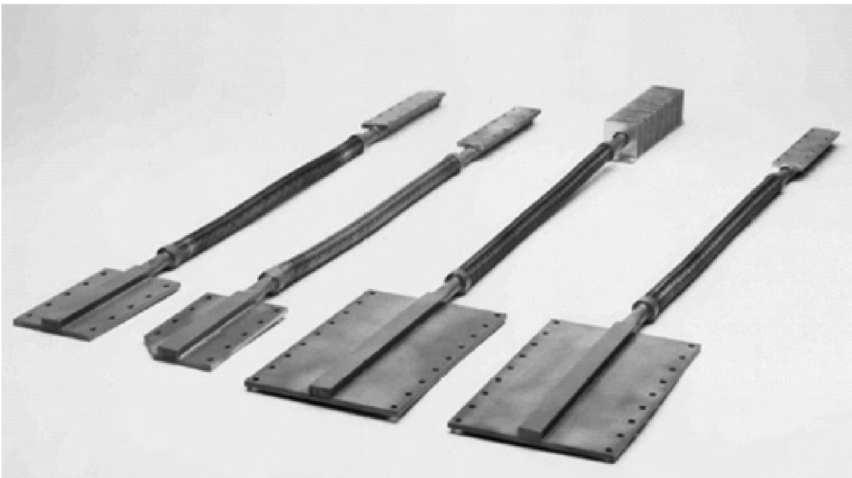

Figure 2.11: A family of flexible heat pipes, used in aircraft[4]

2.6 Heat Transfer Limitations

The heat pipe's heat exchange restrict is the greatest heat that can be exchanged by heat pipe under about isothermal conditions. On the off chance that the heat added to heat pipe surpasses the point of confinement, than the vapor-fluid cycle inside heat pipe ends up plainly exasperates and toward the end dry-out can happen in evaporator area.

With the dry out, the evaporator can never again be provided with fluid and the heat pipe can't keep on transferring heat. The heat exchange constrain relies upon working temperature, thermo-physical properties of working liquid, the wick structure and size and state of heat pipe. The heat exchange cutoff points of heat pipe are;

1. Capillary Limit
2. Viscous Limit
3. Entrainment Limit
4. Sonic Limit
5. Boiling Limit

For every single working temperature, and natural conditions, one of those points of confinement is the deciding variable for the execution of the heat pipe. For instance, at bring down working temperatures, gooey point of confinement ends up noticeably imperative however at typical working temperatures, slim farthest point is more critical and at some higher temperatures, different cutoff points end up plainly essential for the execution of the heat pipe. The change focuses between these breaking points rely upon the kind of working liquid utilized as a part of the heat pipe.[36]

The lowest restrict among the all imperatives characterizes the greatest heat transport limitation of a heat pipe at a given temperature.

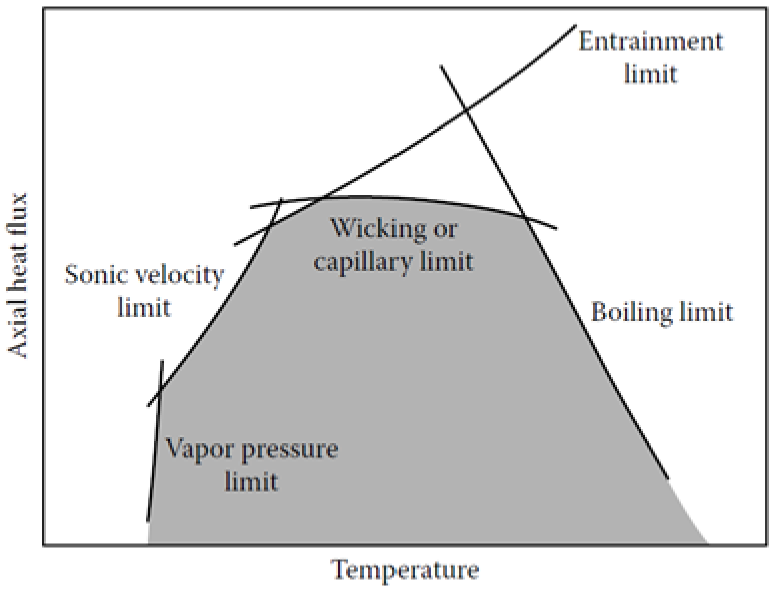

Figure 2.12: Heat Transfer Limitations in Heat Pipe[2]

2.6.1 Capillary Heat Transport Limitation

The capacity of a specific narrow structure to give the flow to a given working liquid is restricted. The farthest point is normally called fine confinements or hydrodynamic impediment. As far as possible is the most regularly experienced restriction in the operation of ordinary temperature heat pipes. It happens when the narrow pumping rate isn't adequate to give enough fluid to the evaporator area. This is because of the way that the entirety of liquid,vapour and gravitational weight drops surpass the greatest slim weight that wick can maintain. The most extreme slim weight for a given wick structure is relies on the physical properties of the wick and the working liquid. Any endeavor to expand the heat exchange over as far as possible will cause dry out in the evaporator area where a sudden increment in divider temperature along the evaporator segment happens.
The essential condition to keep dry out from the evaporator segment is given by,

$$\Delta P_c \geqq \Delta P_l + \Delta P_v + \Delta P_g \tag{2.2}$$

Where,
ΔP_c is capillary pressure loss.
ΔP_l is liquid pressure loss.
ΔP_v is vapour pressure loss.
$\Delta P_g$is gravitational pressure loss.[37]

2.6.2 Viscous Limit (Vapour Pressure Limit)

Gooey point of confinement relies upon the thick weight misfortunes in vapour stage and the vapour weight of the working liquid. The vapour weight is the power that drives the vapour from evaporator to condenser. At the point when the gooey misfortunes in vapour stage are bigger than the vapour weight, than the vapour can not be headed to condenser and the heat pipe can not work. This farthest point ends up plainly compelling at bring down temperatures where the vapour weight of the working liquid is low.
Numerically, as far as possible can be communicated as;

$$Q_{vis} = \frac{A_v r_v^2 L \rho_v P_v}{16 \mu_v l_{eff}} \tag{2.3}$$

Where,

A_v is vapour core area.

r_v is vapour core radius.

L is latent heat of working fluid.

ρ_v is vapour density.

P_v is vapour pressure.

μ_v is vapour viscosity.

l_{eff} is effective length of heat pipe.

Thick breaking point is powerful for the entire areas of the heat pipe, since it relies upon the vapour weight distinction amongst evaporator and condenser segments.[36]

2.6.3 Entrainment Limit

A shear drive exists at the fluid vapour interface since the vapour and fluid move in opposite headings. At high relative speeds, beads of fluid can be torn from wick surface and entrained into the vapour owing toward the condenser area. It will influence stream of fluid towards the evaporator. High speed vapour stream strips and entrains fluid beads in this manner blocking the fluid stream to evaporator. It happens at high stacks and close stop point. On the off chance that the entrainment turns out to be too high, the evaporators will dry-out. The heat exchange rate at which this happens is known as the entrainment limit. Entrainment can be distinguished by the sounds made by the beads striking the condenser end of the heat pipe. As far as possible is regularly connected with low or direct temperature heat pipe with little distance across, or high temperature heat pipes when the heat contribution at the evaporator is high.[37]

The scientific articulation exhibited by Cotter for entrainment restrict is;

$$Q_e = A_v L \sqrt{\frac{\sigma_l P_v}{2 r_{h,w}}} \tag{2.4}$$

Where,

σ_l is liquid surface tension

$r_{h,w}$ is hydraulic radius of the wick.[38]

At the point when the condition for entrainment constrain is researched, clearly as the surface pressure of the liquid is expanded, the farthest point increments, as well. This is relied upon in light of the fact that keeping in mind the end goal to have fluid be included into vapor, thick shear powers amongst fluid and vapour should be higher than the surface strain powers of the fluid. In this manner, as the surface strain of the liquid builds, it ends up plainly increasingly hard to constrain the fluid be included into vapour stream. As far as possible is powerful at the adiabatic area of a heat pipe, where the fluid and vapour stream happens in the meantime.[36]

2.6.4 Sonic Limit

The evaporator segment of a heat pipe can be spoken to as a consistent zone channel. The vapour speed inside the heat pipe increments relentlessly along the length of the evaporator segment which is because of the logically expanding mass stream and achieves a most extreme at the evaporator exit. This sort of stream administration can be contrasted and a united disparate spout with a most extreme mass stream at exit of evaporator area so one might say that it takes after to the throat of concurrent different spout, where greatest speed of vapour compares to the Mach 1. This greatest speed emerges a basic point of confinement of chocked stream in the heat pipe, so over this heat motion if the heat builds it won't demonstrate increment in mass stream of vapour this sort of cutoff is called as sonic farthest point.

The base hub heat exchange because of the sonic restriction will happen at the base working temperature and can be figured from the condition:

$$Q_s = A_v \rho_v L \sqrt{\frac{\gamma R T_v}{2(\gamma + 1)}} \tag{2.5}$$

Where,

γ is specific heat ratio

and R is gas constant.[39]

2.6.5 Boiling Limit

On the off chance that the spiral heat transition in the evaporator area turns out to be too high, the fluid in the evaporator wick bubbles and the divider temperature turns out to be exorbitantly high. The vapour bubbles that shape in the wick keep the fluid from wetting the pipe divider, which causes problem areas. On the off chance that the bubbling is extreme it dries out the wick in the evaporator which is characterized as bubbling breaking point. A high neighbourhood heat motion that reasons the nucleate bubbling and interferes with the fluid stream in evaporator. Be that as it may, under a low or direct spiral heat motion, low force stable bubbling is conceivable without causing dry-out condition. It ought to be noticed that the bubbling restriction is a spiral heat motion constraint as opposed to hub heat transition confinement.[37]

The scientific expression introduced by Chi (1976)[40] for bubbling point of confinement is

$$Q_b = \frac{2\pi l_e k_{eff} T_v}{(L_{\rho v} ln \frac{r_i}{r_v})} [\frac{2\sigma_l}{r_n} - \Delta P_c] \tag{2.6}$$

Where,

l_e is evaporator section length.

k_{eff} is effective thermal conductivity of the liquid-wick combination.

T_v is vapour temperature.

r_i is inner radius of heat pipe.

r_n is critical nucleation site radius.

2.7 Advantages of Heat Pipe

1. Heat pipes are absolutely uninvolved heat exchange frameworks which having no moving parts to destroy. Slim directing in the wick is created by the heat exchange process and requires no other power or moving parts to pump the condensate working liquid. They require no electrical vitality to work consequently no power utilization.
2. They are exceptionally dependable, support free, commotion free gear. Size of the heat pipe is exceptionally reduced, which settles on them the perfect decision for gadgets applications.
3. A heat pipe evaluated at 10W can convey that heat current with a specific temperature drop T, however T is observed to be pretty much autonomous of the length of the heat pipe.Thus, heat pipes are noteworthy not just for their low heat protection R (little T) yet in addition for the exceedingly surprising property that R is generally free of length.The preferred standpoint of utilizing a heat pipe as opposed to a pole of metal in this manner increments with increasing length.
4. They offer the outline design minimal effort bundling and adaptability since they can be fabricated in various shapes and sizes.
5. Heat pipes have colossally more heat exchange ability than different techniques on a weight and size premise.
6. Heat pipe works attractively in a zero gravity condition.

2.8 Disadvantages of Heat Pipe

a) Heat pipes must be tuned to specific cooling conditions. The decision of pipe material, size and coolant all affect the ideal temperatures in which heat pipes work.
b) When a heat pipe is heated over a specific temperature, the majority of the working liquid in the heat pipe will vapourize and buildup process will stop to happen; in such conditions, the heat pipe's heat conductivity is adequately decreased to heat conduction properties of its strong metal packaging. As the vast majority of the heat pipes are de-

veloped with a metal of higher conductivity, an overheated heat pipe will by and large keep on conducting heat at around heat 1/80th unique conductivity. What's more, underneath a specific temperature, the working liquid won't experience stage change and the heat conductivity will be decreased to that of the metal packaging. One of the key criteria for choosing the working liquid is the coveted operational temperature scope of the application. The lower temperature restrict happens couple of degrees over the point of solidification of the working liquid.
c) Most producers can't manufacture the conventional heat channels with under 3mm breadth due to cutting edge creation procedures required.

2.9 Heat Pipe Applications

The scope of its application is amazingly wide and gigantic. A portion of the fields in which it is widely utilized these days are recorded underneath: **a) Aerospace:**
Low weight punishment, zero support and dependability have made heat pipes extremely alluring segments in the territory of rocket cooling and temperature adjustment. Basic isothermalization is a vital issue as respects circling cosmology tests because of the conceivable distorting from sun oriented heating. Heat channels are additionally being utilized to disperse heat produced electronic segments in satellites.

b) Electronics:
Every single electronic part, from chip to top of the line control converters produce heat and dismissal of this heat is fundamental for their ideal and dependable operation. As electronic outline permits higher throughput in littler bundles, disseminating the heat stack turns into a basic plan factor. A considerable lot of the present electronic gadgets require cooling past the capacity of standard metallic heat sinks. Heat pipes offer a high effectiveness, aloof, conservative heat exchange arrangement and are quickly turning into a standard heat administration apparatus.

c) Heat exchangers:
Increments in the cost of vitality have advanced new strategies for rationing vitality in modern applications. Because of their high heat exchange abilities with no outside power necessities heat pipes are being utilized as a part of heat exchangers for different applications.

d) Medicine and human body temperature control:

One of the freshest applications with extraordinary potential for development is the utilization of heat channels identified with human physiology. A surgical test consolidating a cryogenic heat pipe is utilized to wreck tumours in the human body. The cryoprobe is a hand-held gadget with a repository of fluid nitrogen and a 12-inch heat pipe augmentation, which is kept up at roughly 77K for almost one-half hour. Another application to human with critical development potential concerns the control of body temperature for advantages, for example, aversion of frostbites. [3]

Chapter 3

Experimental Characterization of a Heat Pipe

3.1 Problem Definition

A solution was needed for the thermal control of laptop microprocessors with heat dissipating capacities of up to 25W and heat transport distances (i.e. distance between the heat source and heat sink) of up to 200mm. Due to size compactness of computers the maximum thickness of the heat pipe is limited to 10mm.

3.2 Steady State Tests on A Screen Mesh Heat Pipe

In order to verify the characteristics of the selected heat pipe, experiments for measuring heat transport capacity, effective thermal resistance, effective thermal conductivity and efficiency were conducted. The thermal performance of screen mesh heat pipe with 8mm outer diameter and 200mm length was investigated.

3.2.1 Assumptions for the problem

1. Uniform heating in the evaporator section.
2. Steady heat rejection through condenser section.
3. Steady Sate operation during the entire life of heat pipe.
4. Laminar, incompressible flow for both liquid and vapour.

5. No outgassing occurs from the material of the heat pipe.

3.2.2 Experimental set-up

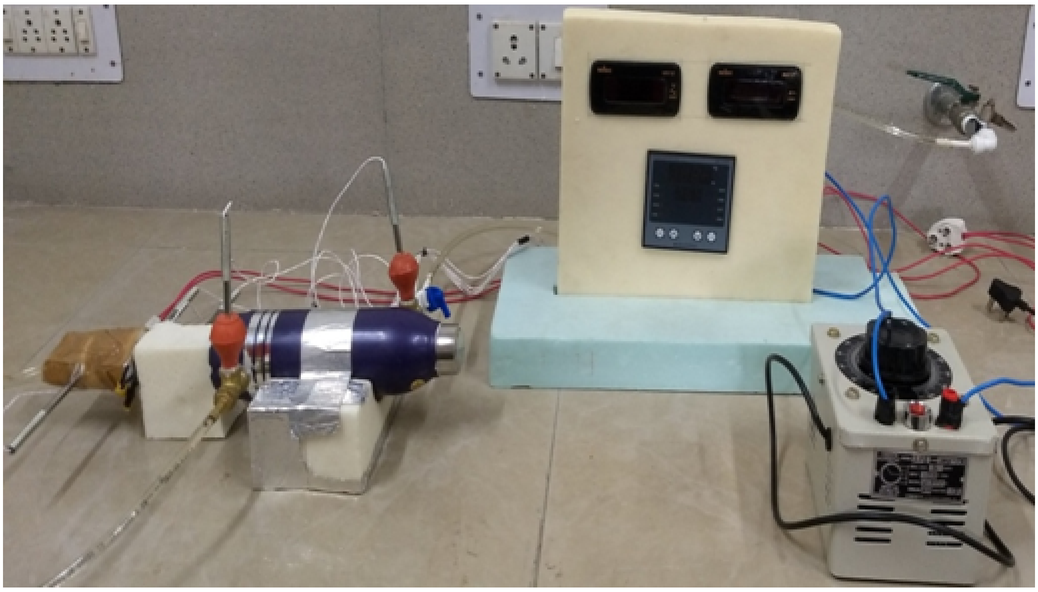

Figure 3.1: Experimental setup of screen meshed heat pipe

An experimental setup for the testing of heat pipe was developed. The main components of the experimental setup are described as following:

a) Heater

At the evaporator section heaters were tightly wrapped on the surface of the flat aluminium bar in which heat pipe was inserted, which provides uniform heat flux to the evaporator section.

b) Power Supply

An AC power supply was used to supply power to the heaters connected at evaporator section. A voltmeter was used to measure an AC voltage.

c) Variac

A variac is used to vary power input by varying current and voltage to the heaters.

d) Copper water heat pipe

A screen meshed water heat pipe of 8mm outer diameter and 200mm length was used to characterize it.

e) Thermocouples

RTD sensors (PT100) were used to measure temperature along the heat pipe and also the temperature of the cooling water. There were 6 sensors, 4 along the length of heat pipe and 2 were used to measure inlet and outlet temperature of the cooling water.

f) Water Jacket

A plastic coated glass water bottle was used to remove heat from the condenser section of heat pipe. Tap water was used to pass through the water jacket which takes away heat from the condenser section.

g) Flow control valves

To control and maintain the flow of cooling water in water jacket, two flow control valves were used at the inlet and outlet section of water jacket. Flow was measured by collecting outlet water in a beaker of known volume and time in which it was collected is recorded.

h) Insulating materials

The evaporator section of heat pipe was insulated using glass wool and tape. This is done to reduce heat loss by convection and radiation to the environment from the experimental setup. The thermal conductivity of glass wool is 0.04W/m-K at 25C.

i) Thermal Grease

Standard Anabond 652c thermally conductive grease was used before attaching thermocouples to the heat pipe and between heat pipe and aluminum block to avoid any air gap.

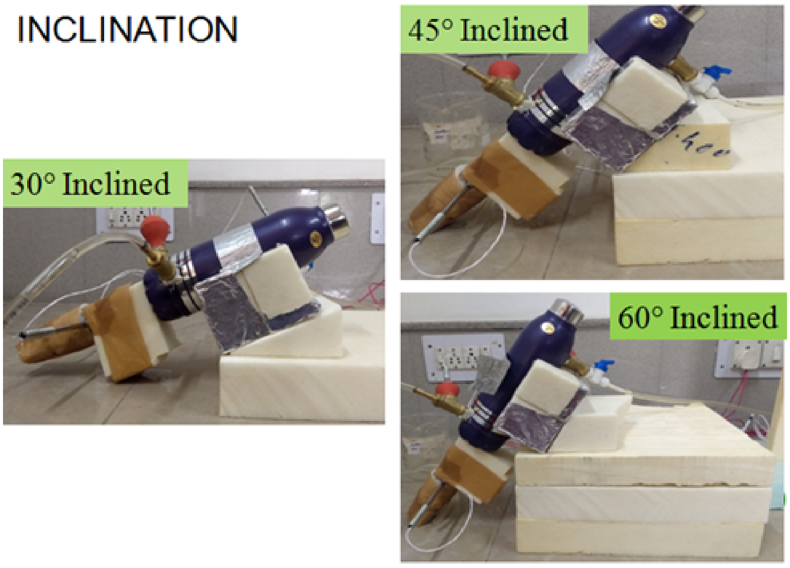

Figure 3.2: Experimental setup of screen meshed heat pipe at different angles of orientation

3.2.3 Specifications of the components

1. Heat Pipe

PARAMETERS	HEAT PIPE SPECIFICATIONS
Container material	Copper
Working fluid	Distilled water
Type of wick	Screen mesh
Wick material	Stainless Steel
Mesh Size	100/inch
Outer diameter	8mm
Wall thickness	0.4mm
Length	200mm
Evaporator length	60mm
Adiabatic length	80mm
Condenser length	60mm
Orientation	Horizontal

Table 3.1: Heat pipe specifications

2. Variac

Maximum Load	2 Amps
Input voltage	240V
Frequency	50Hz
Output voltage	0-270V

Table 3.2: Specifications of Variac

3. Temperature Indicator

Power supply	100-250V AC
Input	PT-100
Temperature range	0 to 400C

Table 3.3: Specifications of Temperature Indicator

4. Voltmeter

Maximum Rated power	5VA
Input voltage	50-480 AC
Frequency	50/60Hz
Output voltage	240V AC

Table 3.4: Specifications of Voltmeter

5. Ammeter

Input	5A AC
Aux. supply	240V AC

Table 3.5: Specifications of Ammeter

3.2.4 Experimental Investigation

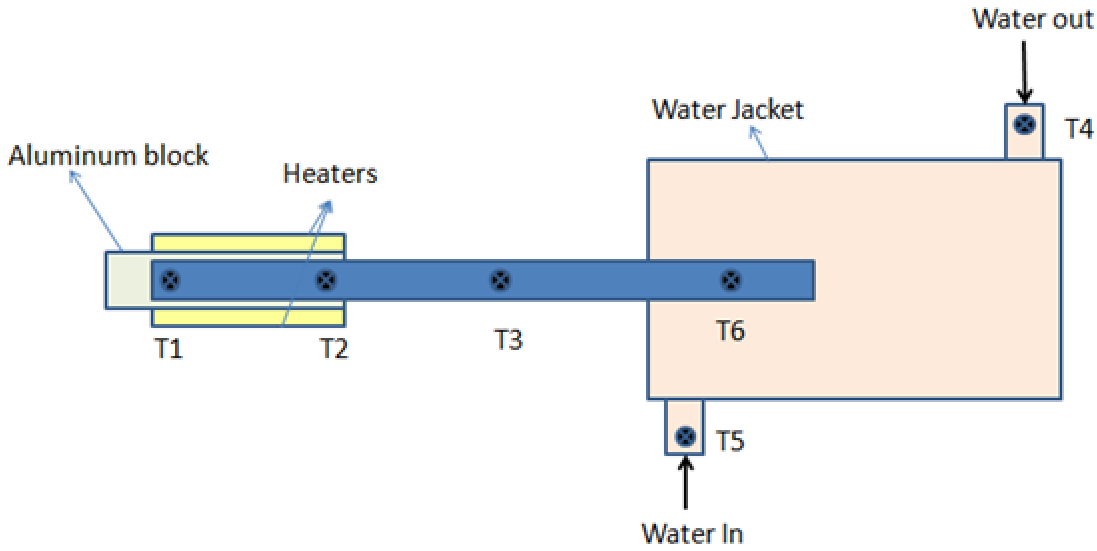

Figure 3.3: Schematic diagram of an experimental setup of screen meshed heat pipe

An experimental apparatus for the heat pipe performance test is composed of the evaporator section, the adiabatic section and the condensed section. At the evaporator section two flat heaters were wrapped on the aluminium block inside which heat pipe is inserted and inside the aluminium block two thermocouples were mounted to measure temperature of the surface of the heat pipe. A thermocouple is mounted in the adiabatic section. Similarly a thermocouple is mounted in the condenser section. The associated heat loss increases the operating temperature of the heat pipe increases to account for this heat loss temperature at the inlet and outlet and the flow rate of cooling water was measured. Heat loss can be calculated as:

$$Q = mC_p(T_{out} - T_{in}) \tag{3.1}$$

Where,

T_{out} and T_{in} is the outlet an inlet temperature of the cooling water flow respectively.

C_p is the specific heat of water .

m is the mass rate of water which can be calculated by collecting water in a beaker of known volume.

3.2.5 Experimental procedure

a) A constant temperature cooling water flow was started through water jacket.

b) The constant temperature cooling water flow rate was measured by collecting water in a beaker and measuring time period.

c) Initially 5 W heat input was given to the evaporator section by supplying the power to the heaters.

d) Once the steady state was reached the temperature readings were noted. Steady state was considered when there was no temperature change in time period of 2 minutes also the inlet and outlet temperature of the cooling water was measured to calculate the heat removal rate. Again heat input was increase in step of 5 watts up to 25 watts.

e) All the temperatures of the experimental apparatus were recorded and effective thermal conductivity, effective thermal resistance and efficiency were calculated.

f) All steps were repeated for various angles of orientation i.e. 0, 30, 45, and 60.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Sample Result

The result obtained by steady state test conducted on the screen meshed horizontal heat pipe is tabulated in Table 4.1.

Sr. No.	Heat Input Qin (W)	Mass flow rate m (kg/sec)	Evaporator temp T1(C)	Evaporator temp T2(C)	Adiabatic temp T3(C)	Water outlet temp T4(C)	Water inlet temp T5(C)	Condenser temp T6(C)
1	5	0.418x10ˆ-3	43.8	44.1	34.7	32.2	30	34.7
2	10	0.418x10ˆ-3	54	54	35.6	34.5	30	35.2
3	15	0.418x10ˆ-3	66.1	65.6	36.2	35.8	30	36
4	20	0.418x10ˆ-3	80.5	79.2	39.3	38	30	39
5	25	0.418x10ˆ-3	91	90	41	40	30	40.6

Table 4.1: Experimental results of temperature and mass flow rate

Axial temperature distribution

The basis for judging the two phase flow and phase change heat transfer process inside the heat pipe is the axial temperature distribution. Therefore the study on heat pipes heat transfer characteristics should proceed with its actual temperature distribution.

Temperature was measured at various applied heat loads during performance test. Figure shows a typical axial temperature distribution along the length of pipe at different heat loads.

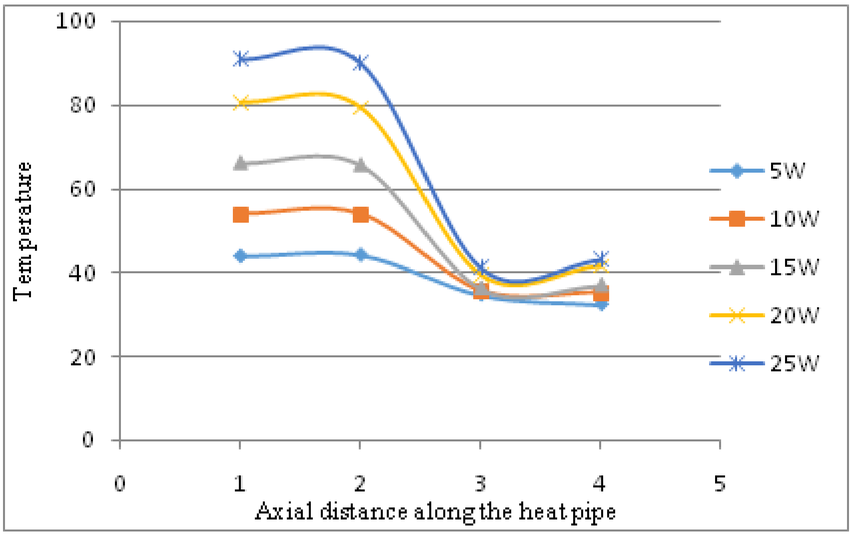

Figure 4.1: Axial temperature distribution for horizontal pipe at different heat loads

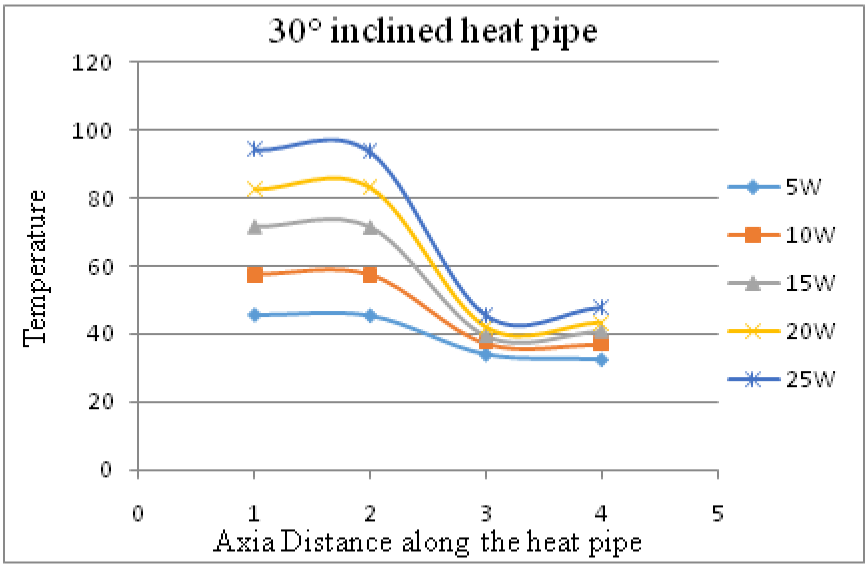

Figure 4.2: Axial temperature distribution for 30°inclined pipe at different heat loads

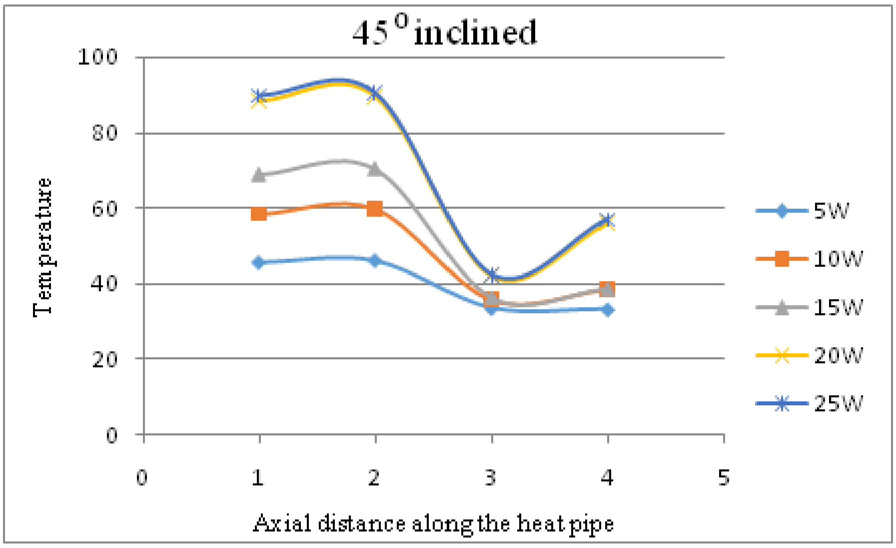

Figure 4.3: Axial temperature distribution for 45°inclined pipe at different heat loads

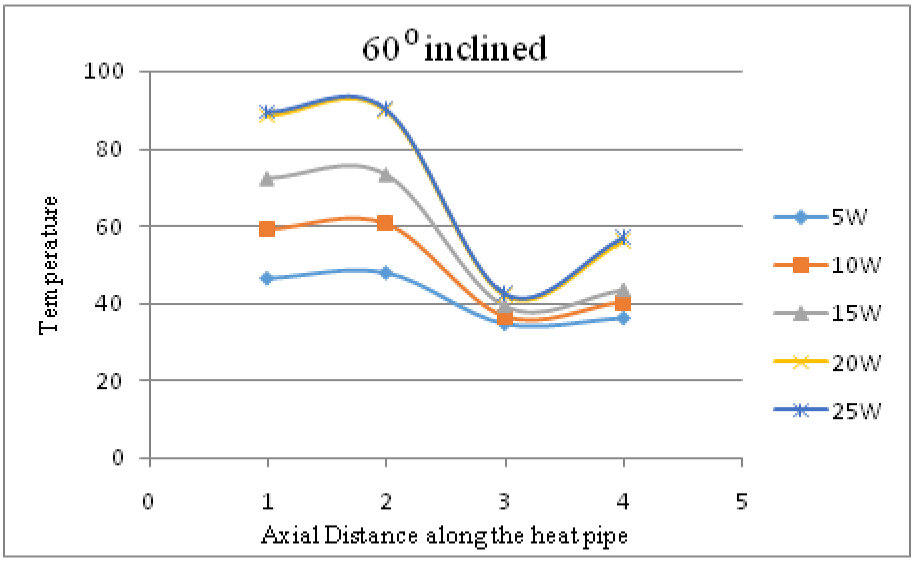

Figure 4.4: Axial temperature distribution for 60°inclined pipe at different heat loads

Effective thermal resistance

One of the important characteristic of screen meshed heat pipe is effective thermal resistance. Thermal resistance can be calculated as follows:

$$R_{th} = \frac{T_e - T_c}{Q_{in}} \tag{4.1}$$

Where,

T_e is evaporator average surface temperature.

T_c is condenser average surface temperature

Q_{in} is heat input

Variation of effective thermal resistance R_{th}(°C/W) v/s heat input (W) is shown below.

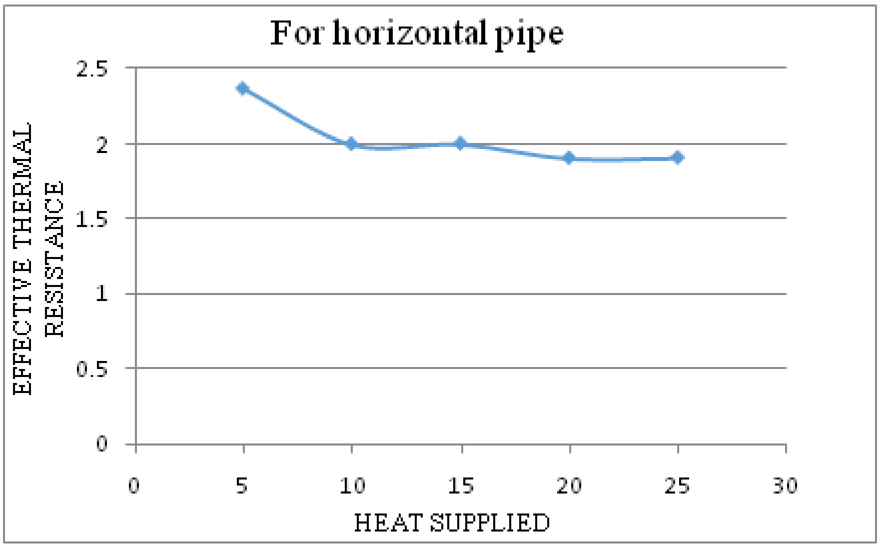

Figure 4.5: Variation of Effective thermal resistance of a horizontal heat pipe

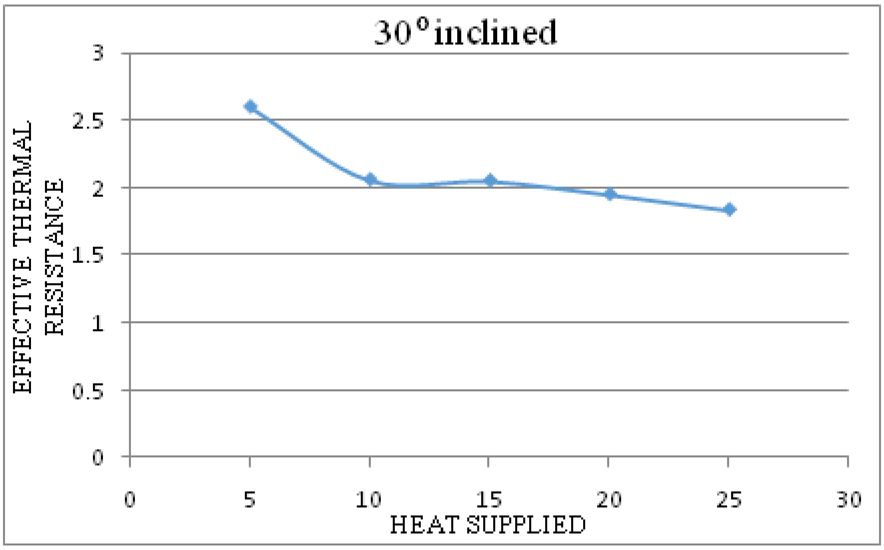

Figure 4.6: Variation of Effective thermal resistance of a 30°C inclined heat pipe

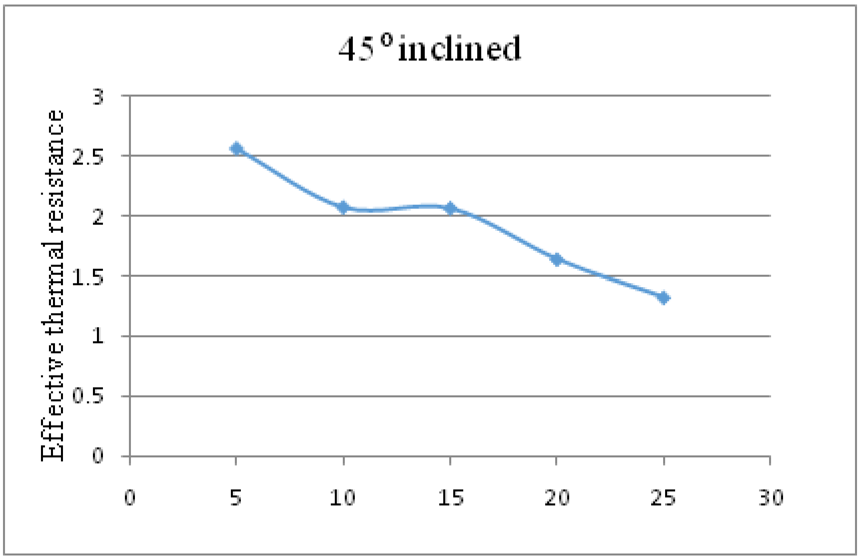

Figure 4.7: Variation of Effective thermal resistance of a 45°C inclined heat pipe

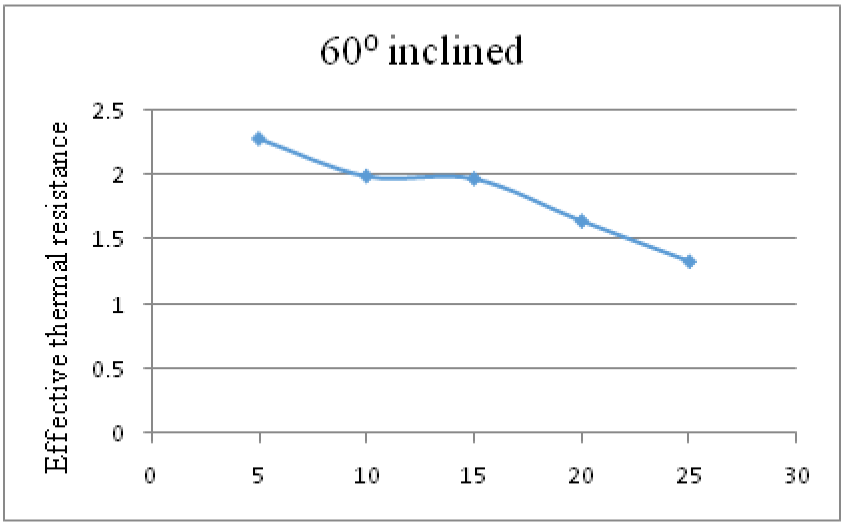

Figure 4.8: Variation of Effective thermal resistance of a 60°C inclined heat pipe

Effective thermal conductivity

Experimental value of effective thermal conductivity can be calculated as:

$$K_{th} = \frac{\ln(r_o/r_i)}{2\pi R_{th} L} \tag{4.2}$$

where,

r_o = Outer radius of heat pipe

r_i = Inner radius of heat pipe

R_{th} = Effective thermal resistance of the heat pipe

L = Length of the heat pipe

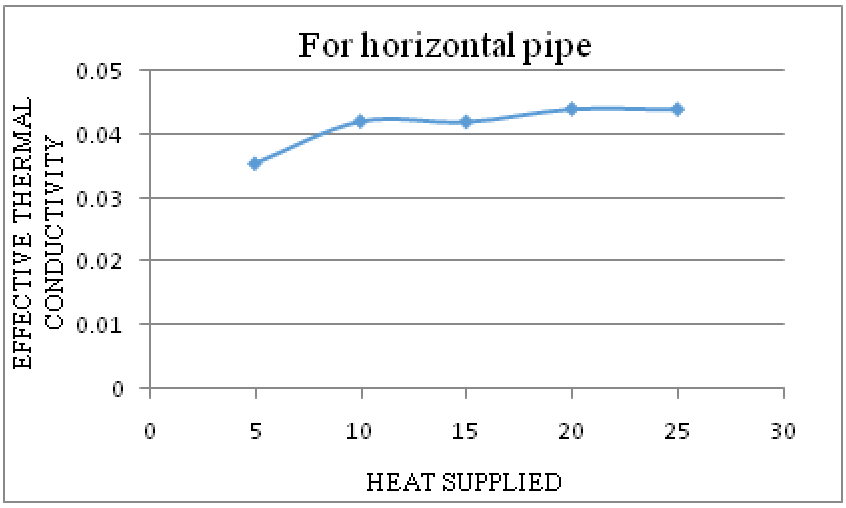

Figure 4.9: Variation of Effective thermal conductivity of a horizontal heat pipe

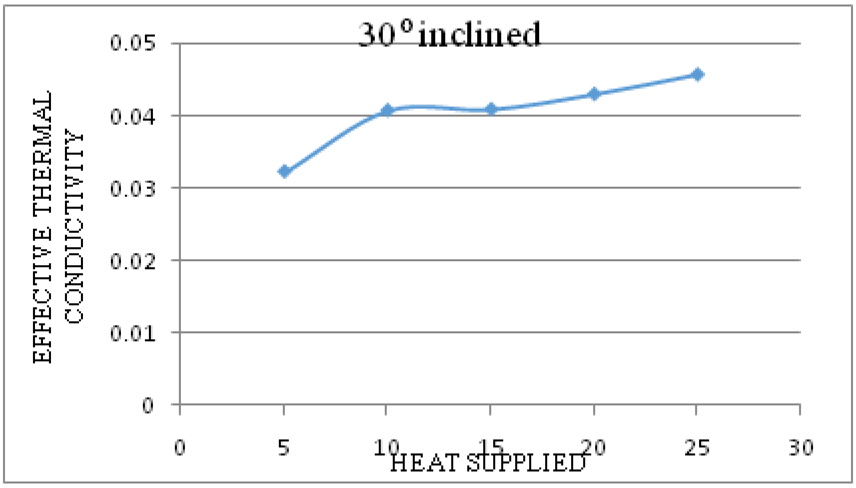

Figure 4.10: Variation of Effective thermal conductivity of a 30°C inclined heat pipe

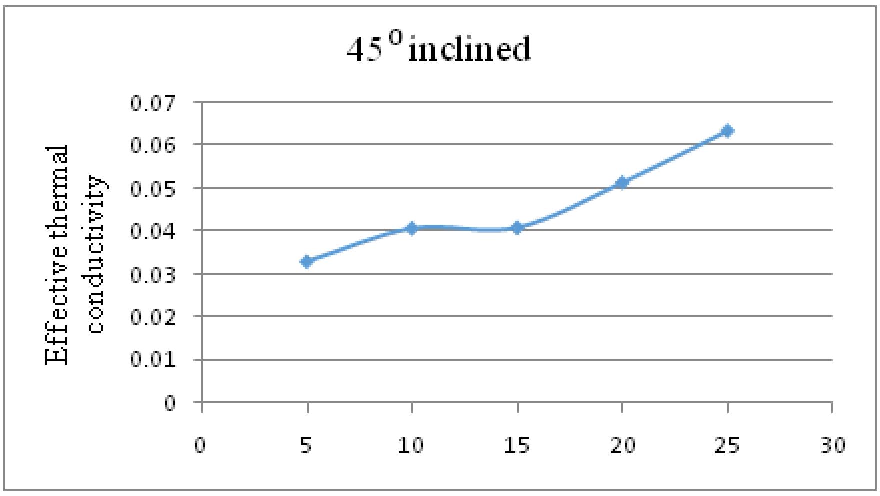

Figure 4.11: Variation of Effective thermal conductivity of a 45°C inclined heat pipe

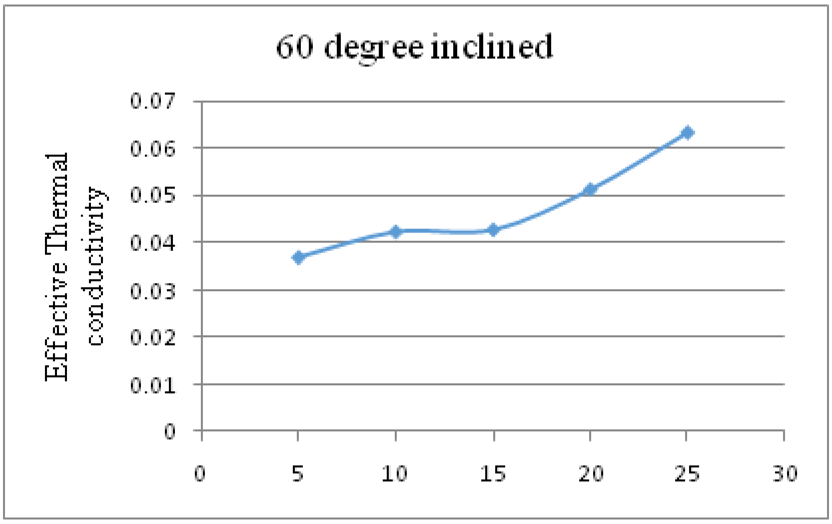

Figure 4.12: Variation of Effective thermal conductivity of a 60°C inclined heat pipe

Efficiency of heat pipe

Efficiency of heat pipe can be calculated as:

$$\eta = \frac{Q_{out}}{Q_{in}} \tag{4.3}$$

where,

Q_{out} = heat removed at condenser section and can be calculated as:

$Q_{out} = mC_p\Delta T$

Q_{in} = heat supplied at evaporator section

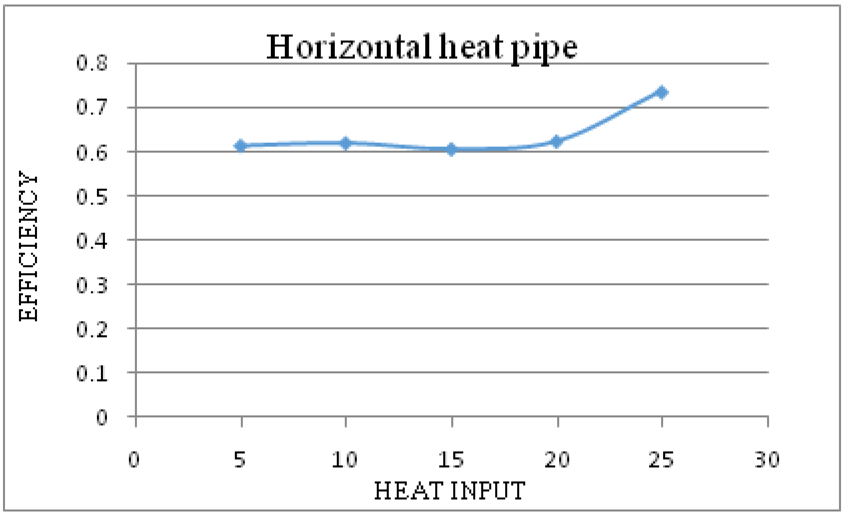

Figure 4.13: Variation of Efficiency of horizontal heat pipe

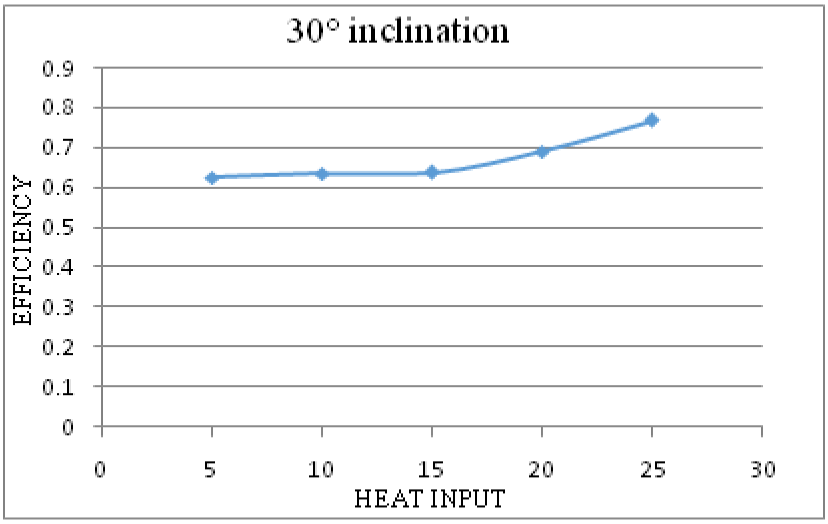

Figure 4.14: Variation of Efficiency of 30°C inclined heat pipe

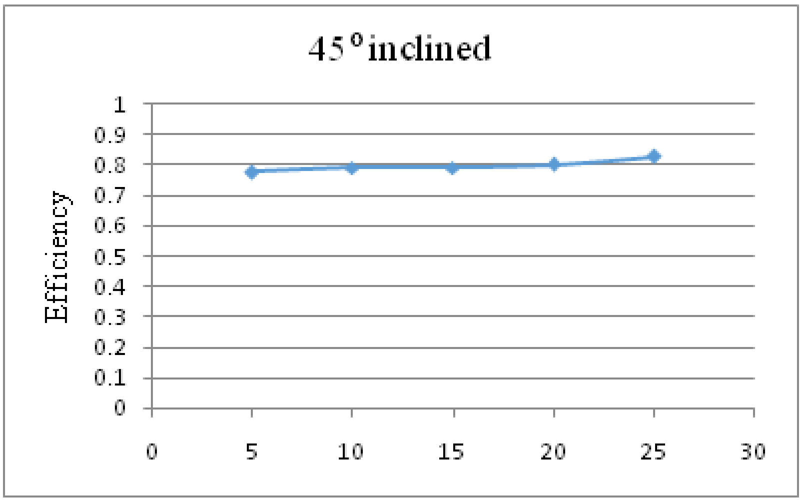

Figure 4.15: Variation of Efficiency of 45°C inclined heat pipe

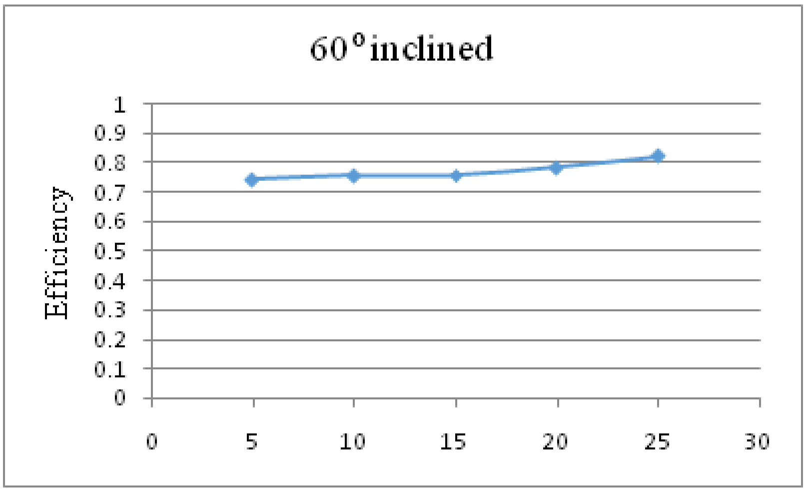

Figure 4.16: Variation of Efficiency of 60°C inclined heat pipe

4.2 Comparison of various parameters

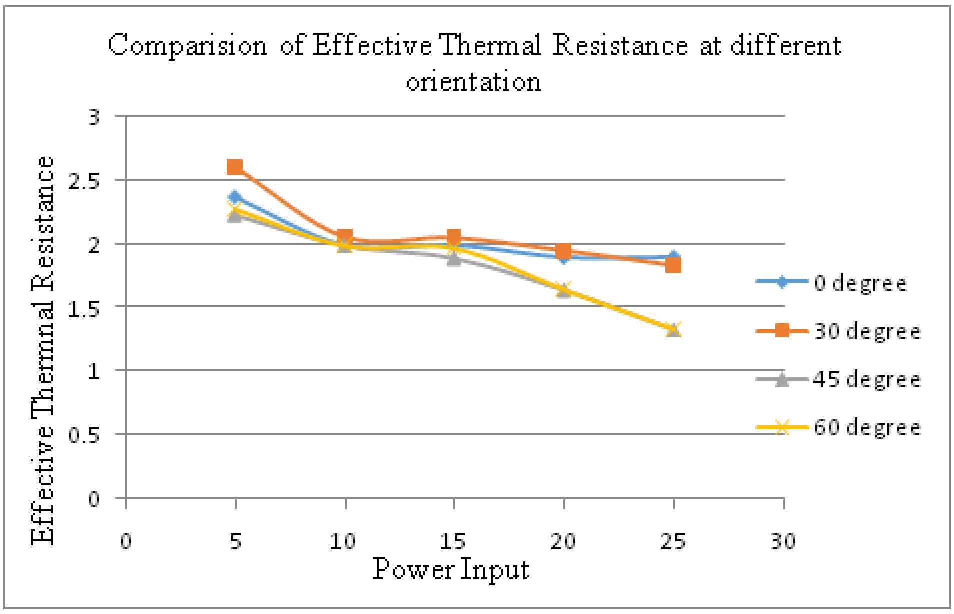

Figure 4.17: Comparison of Effective Thermal Resistance at different orientation

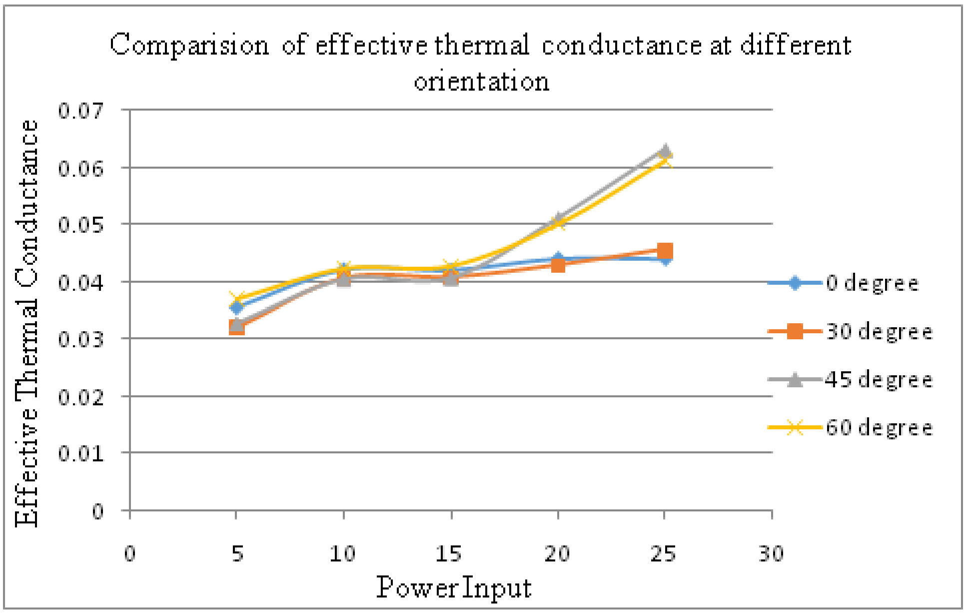

Figure 4.18: Comparison of Effective Thermal Conductance at different orientation

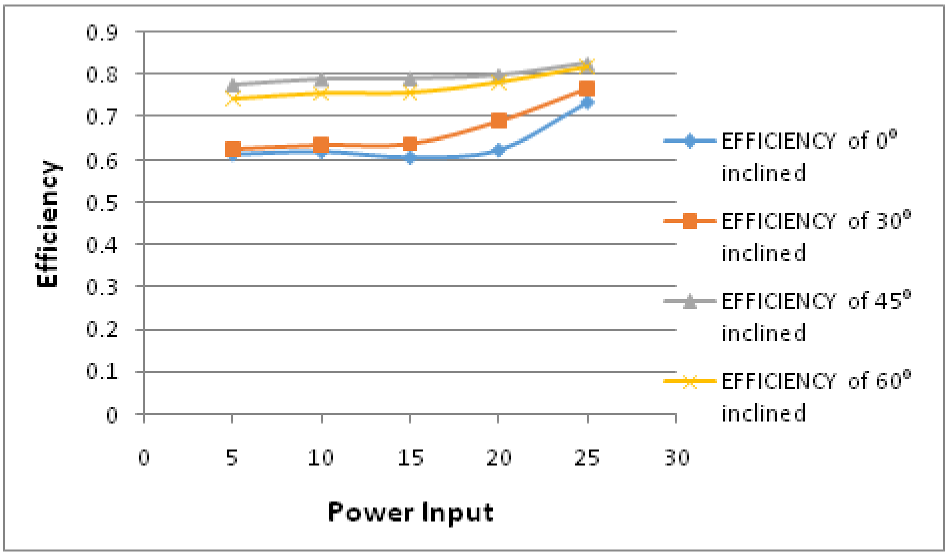

Figure 4.19: Comparison of Efficiency at different orientation

The present heat pipe is cut to investigate various parameters like mesh size, wire diameter of mesh, surface roughness, thickness of heat pipe and filling ratio.

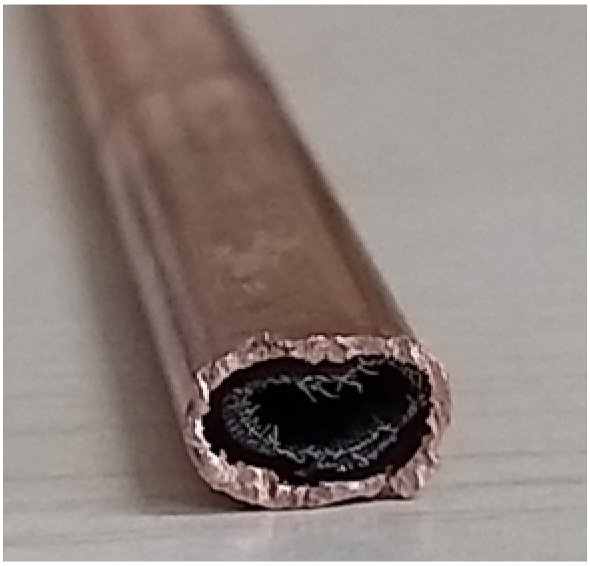

Figure 4.20: Sectional view of heat pipe

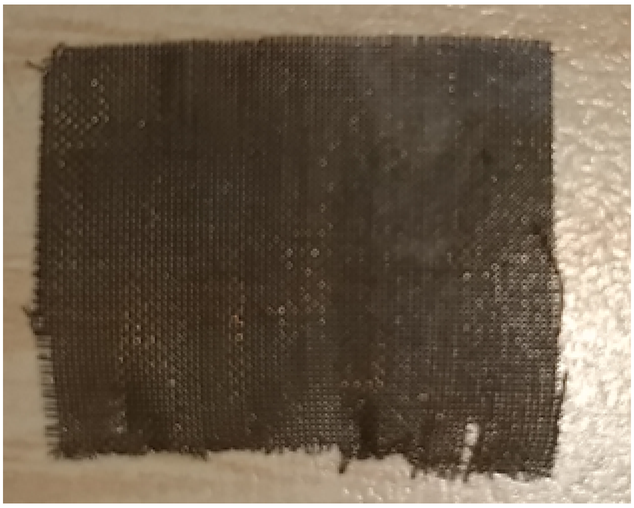

Figure 4.21: Mesh of heat pipe

Surface roughness

The surface roughness at both internal sections i.e. evaporator and condenser plays an important role in heat transfer performance of heat pipe. Higher roughness at the evaporator section increases rate of boiling and lower roughness at the condenser section increases rate of condensation. Hence the roughness of the present heat pipe is measured.

Figure 4.22: Measurement of surface roughness of heat pipe

Sr. No.	Sampling length	Surface roughness (m)
1	5mm	0.368
2	5mm	0.588
3	5mm	0.307

Table 4.2: Results of measurement of surface roughness

The various parameters of the heat pipe are investigated and are listed below:

Sr. No.	Parameter	Value
1	Mesh Size	100/inch
2	No of layers	1
3	Filling ratio	12%
4	Thickness of heat pipe	0.5mm
5	Surface Roughness	0.421
6	Wire diameter of mesh	0.00011m

Table 4.3: Investigated parameters of heat pipe

4.3 Calculation of wick parameters

In the present work we have selected 100 mesh stainless steel wire mesh wick as compatible with copper container.

Wick size, N = 100/inch= 3937 m^{-1}

Wire diameter d_w = 0.011 mm = 11 $\times 10^{-5}$ m

Wick thickness t_w = 0.6 mm = 0.6×10^{-4} m

Taking single layer of 100 mesh size,

$$D_i = D_v + 2 \times no.oflayers \times t_w \tag{4.4}$$

$$7.2 \times 10^{-3} = D_v + 2 \times 6 \times 10^{-5}$$
$$D_v = 7.08 \times 10^{-3}\text{m}$$

Vapour core flow area,

$$A_v = \frac{\pi}{4} D_v^2 \tag{4.5}$$

$$A_v = 3.936 \times 10^{-5} m^2$$

Effective length of heat pipe,

$$l_{eff} = 0.5 l_e + l_a + 0.5 l_c \tag{4.6}$$

$$l_{eff} = 0.5 \times 0.06 + 0.08 + 0.5 \times 0.06$$
$$l_{eff} = 0.14\text{m}$$

Wick cross sectional area,

$$A_w = \frac{\pi}{4}(D_i^2 - D_v^2) \tag{4.7}$$

$$A_w = 3.14/4 \times (7.2^2 - 7.08^2) \times 10^{-6}$$
$$A_w = 1.3458 \times 10^{-6} m^2$$

Wick Porosity,

$$\epsilon = 1 - \frac{1.05 \pi N d_w}{4} \tag{4.8}$$

$$\epsilon = 1 - \tfrac{1.05 \times \pi \times 3937 \times 11 \times 10^{-5}}{4}$$
$$\epsilon = 0.632$$

Wick Permeability(K),

$$K = \frac{d_w^2 P_w^2}{122(1 - P_w)^2} \tag{4.9}$$

$$P_w = \frac{(11 \times 10^{-5})^2 \times 0.632^2}{122(1 - 0.632)^2}$$

$$P_w = 1.93 \times 10^{-10} \text{ m}^2$$

Capillary radius(r_c),

$$r_c = \frac{1}{2N} \tag{4.10}$$

$$r_c = \frac{1}{2 \times 3937}$$

$$r_c = 12.7 \times 10^{-5} \text{ m}$$

Effective thermal conductivity of wick,

$$K_{eff} = \frac{K_f[K_f + K_s - (1 - \epsilon)(K_f - K_s)]}{K_f + K_s + (1 - \epsilon)(K_f - K_s)} \tag{4.11}$$

where,

k_f = Thermal conductivity of fluid

K_s = Thermal conductivity of solid

$$K_{eff} = \frac{0.591[0.591 + 16.2 - (1 - 0.632)(0.591 - 16.2)]}{0.591 + 16.2 + (1 - 0.632)(0.591 - 16.2)}$$

$$K_{eff} = 1.2056 \text{ W/m K}$$

Wick material	Stainless steel
Mesh number(mesh/inch)	100
Screen wire diameter(mm)	0.11
Screen wick thickness (mm)	0.6
Porosity	0.632
Permeability(m^2)	1.93 $\times 10^{-10}$
Capillary radius(m)	12.7 $\times 10^{-5}$
Effective thermal conductivity of wick (W/m K)	1.2056

Table 4.4: Design summary of screen mesh wick

4.4 Calculation of Heat transfer limitations

Taking thermophysical properties of water at 40 C,

Properties	Value
L(J/kg)	240210^3
$\rho_l(kg/m^3)$	992.3
$\rho_v(kg/m^3)$	0.05
$\mu_l(Pas)$	0.000825
$\mu_v(Pas)$	0.00001
$\sigma_l(N/m)$	6.9610^{-2}
$P_v(N/m^2)$	5000
Molecular Weight (w_m)	18
Gas Constant R=8134/w_m	462
$\gamma = Cp/Cv$	1.33

Table 4.5: Properties of water

Figure of Merit / Liquid transport factor

$$M = \frac{\rho_l \sigma_l L}{\mu_l}$$
$$M = (6.96 \times 10^{-2} \times 992.3 \times 2402 \times 10^3)/0.000825 \tag{4.12}$$
$$M = 2.01 \times 10^{11} W/m^2$$

Capillary Limit

$$\Delta P_c = \frac{2\sigma_l}{r_c} \tag{4.13}$$

$$\Delta P_c = 2196.06 N/m^2$$

Liquid pressure drop can be calculated using following equation:

$$\Delta P_l = \frac{\mu_l}{\rho_l L} \times \frac{Q_c L_{eff}}{A_w K}$$
$$\Delta P_l = \frac{0.825 \times 10^{-3}}{992.3 \times 2402 \times 10^3} \times \frac{Q_c 0.14}{1.3458 \times 10^{-6} \times 1.93 \times 10^{-10}} \tag{4.14}$$
$$\Delta P_l = 86.56 Q_c N/m^2$$

Vapour pressure drop can be calculated as:

$$\Delta P_v = \frac{8\mu_v Q_c l_{eff}}{L\rho_v \pi r_v^4}$$
$$\Delta P_v = \frac{8 \times 10^{-5} \times Q_c \times 0.14}{2402 \times 10^3 \times 0.05 \times \pi \times (3.54 \times 10^{-34})} \tag{4.15}$$
$$\Delta P_v = 0.189 Q_c N/m^2$$

Gravitational pressure drop:

$$\Delta P_g = \rho_l g D_v$$
$$\Delta P_g = 992.3 \times 9.81 \times 7.08 \times 10^{-3} \tag{4.16}$$
$$\Delta P_g = 68.919 N/m^2$$

The limiting flux Q_c,

$$\Delta P_c = \Delta P_l + \Delta P_v + \Delta P_g$$
$$2196.06 = 86.56 Q_c + 0.18902 Q_c + 68.919 \tag{4.17}$$
$$Q_c = 26.52 W$$

Reynold's No. for vapour flow can be calculated as:

$$Re_v = \frac{D_v Q_c}{A_v L \mu_v}$$
$$Re_v = \frac{7.08 \times 10^{-3} \times 26.52}{2.936 \times 10^{-5} \times 2402000 \times 10^{-5}} \tag{4.18}$$
$$Re_v = 266.242300$$

Mach No,

$$M_v(max) = \frac{Q_c}{A_v L \rho_v \sqrt{\Gamma R_g T_v}}$$
$$= \frac{26.52}{2.936 \times 10^{-5} \times 2402000 \times 0.05 \sqrt{1.33 \times 462 \times 313}} \tag{4.19}$$
$$= 0.0171$$

Entrainment limit

$$Q_e(max) = A_v L \sqrt{\frac{\sigma_l \rho_v}{2 r_{h,w}}}$$
$$r_{h,w} = \frac{A_w}{\pi(D_v + D_i)}$$
$$= \frac{1.3458 \times 10^{-6}}{\pi(7.08 + 7.2) \times 10^{-3}} \tag{4.20}$$
$$= 2.99 \times 10^{-5}$$
$$Q_e(max) = 2.936 \times 10^{-5} \times 2402000 \sqrt{\frac{6.96 \times 10^{-2} \times 0.05}{2 \times 2.99 \times 10^{-5}}}$$
$$Q_e(max) = 537.98W$$

Sonic limit The sonic limit is calculated on the minimum operating temperature which is taken 20°.

Hence properties of water at 20°C are taken.

L=2248

ρ_v= 0.02

$$Q_s = A_v \rho_v L \sqrt{\frac{\gamma R T_v}{2(\gamma + 1)}}$$
$$= 2.936 \times 10^{-5} \times 0.05 \times 2448 \times 10^3 \sqrt{\frac{1.33 \times 462 \times 293}{2(1.33 + 1)}} \tag{4.21}$$
$$Q_s = 706.35W$$

Viscous limit

$$Q_{vis} = A_v L D_v^2 \frac{\rho_v P_v}{64 l_e \mu_v}$$
$$Q_{vis} = 2.936 \times 10^{-5} \times 2402000 \times (7.08 \times 10^{-3})^2 \frac{7000 \times 0.05}{64 \times 0.07 \times 10^{-5}} \tag{4.22}$$
$$Q_{vis} = 27617.57W$$

Boiling limit

$$Q_b = \frac{2\pi l_e K_{eff} T_v}{L\rho_v \ln(D_i/D_v)}[\frac{2\sigma_l}{r_n} - P_e]$$
$$= \frac{2\pi \times 0.07 \times 1.2056 \times 313}{2402 \times 10^3 \times 0.05 \times \ln(7.2/7.08)}[\frac{2 \times 6.96 \times 10^{-2}}{10^{-7}} - 2242.52] \tag{4.23}$$
$$Q_b = 23320.19W$$

Heat transfer limits	**Value**
Capillary limit	2196.06 N/m^2
Entrainment limit	537.98W
Sonic limit	706.35W
Viscous limit	27617.57W
Boiling limit	23320.19W

Table 4.6: Calculated heat transfer limits

Chapter 5

Conclusion and Future scope

5.1 Conclusion

The following conclusions are derived from the present work:

1. The effective thermal resistance of heat pipe is decreases as heat input increases. The maximum value of effective thermal resistance is found to be 2.23564 K/W at 5W heat input while its minimum value is 1.3277 K/W at heat load of 25W.

2. The Effective Thermal Conductance increases with increase in heat input.The minimum and maximum value of effective thermal conductivity is 0.03218 W/mK and 0.06317W/mK at heat input of 5W and 25W respectively.

3. Efficiency of the heat pipe is in the range of 60-63% for lower heat input (5-15W) while it lies in the range of 79-82.7% for high heat input(20-25W).

4. The orientation of heat pipe at 45°(gravity assisted- condenser oriented upwards) performed most efficiently and the average improvement was 25.19% with respect to the horizontal position of heat pipe. Also, the lowest value of effective Thermal resistance and highest value of effective thermal conductivity is obtained at 45°angle of orientation

5.2 Future Scope

The following work may be considered for further extension of the present project:

1. Surface enhancement can be carried out by changing surface roughness of evaporator and condenser section of heat pipe and performance can be checked.

2. Test can be conducted to analyze effect of different thickness of flattening on heat pipe and optimum solution would be suggested.

3. User defined function can be written to simulate evaporation and condensation simultaneously inside the heat pipe and hence CFD analysis can be carried out.

Bibliography

[1] S. S. Anandan and V. Ramalingam, “Thermal management of electronics: A review of literature,” 2008.

[2] B. Zohuri, *Heat pipe design and technology.* Springer, 2011.

[3] A. Engelhardt, *Investigation of several critical issues in screen mesh heat pipe manufacturing and operation.* PhD thesis, University of Nottingham, 2010.

[4] D. Reay, R. McGlen, and P. Kew, *Heat pipes: theory, design and applications.* Butterworth-Heinemann, 2013.

[5] “Thermacore heat pipe reliability document,” March 2014.

[6] R. Matthews, “Mechanical engineer’s handbook: Energy and power, vol. 4, chpt. 27, feb. 16, 2006.”

[7] C. Lasance, “The need for a change in thermal design philosophy,” *Electronics Cooling*, vol. 1, no. 2, pp. 24–26, 1995.

[8] . R. Gaugler, “heat pipe devices,” *United States Patent Office*, pp. 348–350, 1944.

[9] G. M. Grover, “Evaporation-condensation heat transfer device,” Jan. 18 1966. US Patent 3,229,759.

[10] T. Cotter, “Principles and prospects for micro heat pipes,” tech. rep., Los Alamos National Lab., NM (USA), 1984.

[11] A. Faghri, “Heat pipes: review, opportunities and challenges,” *Frontiers in Heat Pipes (FHP)*, vol. 5, no. 1, 2014.

[12] Y.-W. Chang, C.-H. Cheng, J.-C. Wang, and S.-L. Chen, "Heat pipe for cooling of electronic equipment," *Energy Conversion and Management*, vol. 49, no. 11, pp. 3398–3404, 2008.

[13] S. H. Moon, G. Hwang, H. G. Yun, T. G. Choy, and Y. I. Kang, "Improving thermal performance of miniature heat pipe for notebook pc cooling," *Microelectronics Reliability*, vol. 42, no. 1, pp. 135–140, 2002.

[14] K. A. Joudi and A. Witwit, "Improvements of gravity assisted wickless heat pipes," *Energy conversion and management*, vol. 41, no. 18, pp. 2041–2061, 2000.

[15] S. Shibayama and S. Morooka, "Study on a heat pipe," *International Journal of Heat and Mass Transfer*, vol. 23, no. 7, pp. 1003–1013, 1980.

[16] A. Mozumder, A. Akon, M. Chowdhury, and S. Banik, "Performance of heat pipe for different working fluids and fill ratios," *Journal of Mechanical Engineering*, vol. 41, no. 2, pp. 96–102, 2011.

[17] A. Faghri, M. Buchko, and Y. Cao, "A study of high-temperature heat pipes with multiple heat sources and sinks: Part iexperimental methodology and frozen startup profiles," *Journal of heat transfer*, vol. 113, no. 4, pp. 1003–1009, 1991.

[18] K. Sun, C. Liu, and K. Leong, "The effective length of a flat plate heat pipe covered partially by a strip heater on the evaporator section," *Heat Recovery Systems and CHP*, vol. 15, no. 4, pp. 383–388, 1995.

[19] P. Nemec, A. Caja, and M. Malcho, "Thermal performance measurement of heat pipe," *Global journal of technology and optimization*, vol. 2, no. 1, 2011.

[20] K. Manikandan and R. Senthilkumar, "Optimization of heat pipe container diameter using response surface technology," *Australian Journal of Basic and Applied Sciences*, vol. 9, no. 36, pp. 113–124, 2015.

[21] R. Senthilkumar, K. Manikandan, and M. Velmurugan, "Study of heat pipes using nanofluids in heat recovery and energy conservation systems," *Advances in Natural and Applied Sciences*, vol. 10, no. 4, pp. 514–521, 2016.

[22] K. Shukla, A. B. Solomon, B. Pillai, B. J. R. Singh, and S. S. Kumar, "Thermal performance of heat pipe with suspended nano-particles," *Heat and Mass Transfer*, vol. 48, no. 11, pp. 1913–1920, 2012.

[23] M. Ghanbarpour, N. Nikkam, R. Khodabandeh, and M. Toprak, "Thermal performance of inclined screen mesh heat pipes using silver nanofluids," *International communications in heat and mass transfer*, vol. 67, pp. 14–20, 2015.

[24] T. Brahim, M. H. Dhaou, and A. Jemni, "Theoretical and experimental investigation of plate screen mesh heat pipe solar collector," *Energy conversion and management*, vol. 87, pp. 428–438, 2014.

[25] P. r. Bhoomipagu Alankritha, "Thermal performance of a square copper heat pipe for different volumes of cuo nanofluid," *International journal of innovative Research in science, engineering and technology*, vol. 4, pp. 7714–7721, 2015.

[26] R. Senthilkumar, S. Vaidyanathan, and B. Sivaraman, "Effect of inclination angle in heat pipe performance using copper nanofluid," *Procedia engineering*, vol. 38, pp. 3715–3721, 2012.

[27] C. Loh, E. Harris, and D. Chou, "Comparative study of heat pipes performances in different orientations," in *Semiconductor Thermal Measurement and Management Symposium, 2005 IEEE Twenty First Annual IEEE*, pp. 191–195, IEEE, 2005.

[28] T. Yousefi, S. Mousavi, B. Farahbakhsh, and M. Saghir, "Experimental investigation on the performance of cpu coolers: Effect of heat pipe inclination angle and the use of nanofluids," *Microelectronics Reliability*, vol. 53, no. 12, pp. 1954–1961, 2013.

[29] H.-Z. Tao, H. Zhang, J. Zhuang, and W. J. Bowman, "Experimental study of heat transfer performance in a flattened aghp," *Applied Thermal Engineering*, vol. 28, no. 14-15, pp. 1699–1710, 2008.

[30] L. Jiang, Y. Huang, Y. Tang, Y. Li, W. Zhou, L. Jiang, and J. Gao, "Fabrication and thermal performance of porous crack composite wick flattened heat pipe," *Applied Thermal Engineering*, vol. 66, no. 1-2, pp. 140–147, 2014.

[31] Y. Li, J. He, H. He, Y. Yan, Z. Zeng, and B. Li, "Investigation of ultra-thin flattened heat pipes with sintered wick structure," *Applied Thermal Engineering*, vol. 86, pp. 106–118, 2015.

[32] K.-T. Lin and S.-C. Wong, "Performance degradation of flattened heat pipes," *Applied Thermal Engineering*, vol. 50, no. 1, pp. 46–54, 2013.

[33] Y. Li, W. Zhou, J. He, Y. Yan, B. Li, and Z. Zeng, "Thermal performance of ultra-thin flattened heat pipes with composite wick structure," *Applied Thermal Engineering*, vol. 102, pp. 487–499, 2016.

[34] G. P. Peterson, "An introduction to heat pipes: modeling, testing, and applications," 1994.

[35] A. Faghri, "Review and advances in heat pipe science and technology," *Journal of heat transfer*, vol. 134, no. 12, p. 123001, 2012.

[36] A. P. D. İ. Tari, *A comparative investigation of heat transfer capacity limits of heat pipes*. PhD thesis, Middle East Technical University, 2007.

[37] A. Faghri, *Heat pipe science and technology*. Global Digital Press, 1995.

[38] G. P. Peterson, "An introduction to heat pipes: modeling, testing, and applications," 1994.

[39] P. Dunn and D. Reay, *Heat pipes*. Elsevier, 2016.

[40] S. Chi, "Heat pipe theory and practice(book)," *Washington, D. C., Hemisphere Publishing Corp.*, 1976.

Appendices

Appendix A

Appendix-I

Uncertainty Analysis

To analyze the reliability of the experiments, uncertainty study is required. Kline and mcClinLock has described the precised method for calculating uncertainties associated with various quantities in an experiment. Uncertainties associated with each derived quantity can be calculated as follows:

Heat input at the evaporator section is the product of voltage and current supplied. Hence heat input is:

$$Q_{in} = VI \tag{A.1}$$

Differentiating above equation w.r.t. V and I, we get:

$$\frac{\partial Q_{in}}{\partial V} = I \tag{A.2}$$

$$\frac{\partial Q_{in}}{\partial I} = V \tag{A.3}$$

Uncertainty equation for heat input can be written as:

$$\omega Q_{in} = \sqrt{(\frac{\partial Q_{in}}{\partial V}\omega_1)^2 + (\frac{\partial Q_{in}}{\partial I}\omega_2)^2} \tag{A.4}$$

where,

ω_1 = uncertainty in measurement of voltage

ω_2 = uncertainty in measurement of current

Uncertainty equation for heat input in percentage can be written as:

$$\omega Q_{in} in(\%) = \frac{\omega Q_{in}}{Q_{in}} \times 100 \tag{A.5}$$

In the similar way uncertainty associated with various quantities can be calculated using equations tabulated in table below.

Quantity	**Equation**	**Uncertainty(%)**
Heat input	$Q_{in} = VI$	0.274
Heat output	$Q_{out} = mC_p\Delta T$	3.84
Effective thermal resistance	$R_{th} = T_e - T_c/Q_{in}$	1.905
Effective thermal conductivity	$K_{th} = \ln(r_o/r_i)/2\pi R_{th}L$	0.85

Table A.1: Uncertainties of calculated quantities

Appendix B

Appendix-II

Water

Temp °C	Latent heat kJ/kg	Liquid density kg/m^3	Vapour density kg/m^3	Liquid thermal conductivity W/m °C	Liquid viscos. cP	Vapour viscos. cP × 10^2	Vapour press. Bar	Vapour specific heat kJ/kg °C	Liquid surface tension N/m × 10^2
20	2448	998.2	0.02	0.603	1.00	0.96	0.02	1.81	7.28
40	2402	992.3	0.05	0.630	0.65	1.04	0.07	1.89	6.96
60	2359	983.0	0.13	0.649	0.47	1.12	0.20	1.91	6.62
80	2309	972.0	0.29	0.668	0.36	1.19	0.47	1.95	6.26
100	2258	958.0	0.60	0.680	0.28	1.27	1.01	2.01	5.89
120	2200	945.0	1.12	0.682	0.23	1.34	2.02	2.09	5.50
140	2139	928.0	1.99	0.683	0.20	1.41	3.90	2.21	5.06
160	2074	909.0	3.27	0.679	0.17	1.49	6.44	2.38	4.66
180	2003	888.0	5.16	0.669	0.15	1.57	10.04	2.62	4.29
200	1967	865.0	7.87	0.659	0.14	1.65	16.19	2.91	3.89

Figure B.1: Properties of water