

**Experimental Investigation of Heat Pipe with Annular Fins under  
Natural Convection at Different Inclinations**

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**Master of Engineering**  
in  
**Thermal Engineering**

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**JUNE, 2018**

## CERTIFICATE

I hereby declare that the thesis report entitled “**Experimental Investigation of Heat Pipe with Annular Fins under Natural Convection at Different Inclinations.**” is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering in Thermal Engineering** at **TIET, Patiala** under the supervision of **Mr. Sumeet Sharma** (Associate Professor, M.E.D) and **Dr. D. Gangacharyulu** (Professor, Ch.E.D). No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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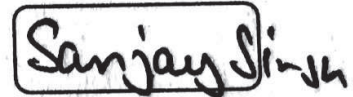
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## Declaration

I, **SANJAY SINGH**, hereby declare that the thesis, entitled “**EXPERIMENTAL INVESTIGATION OF HEAT PIPE WITH ANNULAR FINS UNDER NATURAL CONVECTION AT DIFFERENT INCLINATIONS**”, submitted to **Mechanical Engineering Department, TIET**, in partial fulfilment of the requirements for the award of the degree of **Master of Engineering in Thermal Engineering** is a record of original and independent research work done by me during the period 2016-2018, under the supervision and guidance of **Mr. Sumeet Sharma**, Associate Professor, Mechanical Engineering Department and **Dr.D.Gangacharyulu**, Professor, Department of chemical Engineering. The work contained in this thesis has not been previously submitted to meet the requirements for a degree or diploma at this or any higher education institution.



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*Dedicated to*

*My parents*

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## ABSTRACT

Heat pipe are also characterised as superconductor of heat because of their excellent heat transfer and heat removal ability with minimum heat loss. Numerous research and experimentation has been conducted on heat pipe in 21<sup>st</sup> century due to rapid advancement of electronics equipment's. Gravitational and capillary force play a vital role in thermal performance of heat pipe. In this scenario, cooling of electronics component is a major task in today engineering studies. The operation of several engineering system results in generation of heat. This may cause several overheating problems and lead to failure of the system. To overcome this problem and to achieve desired rate of dissipation as when fins or extended surface are utilizing. So there is need to study the performance of heat pipe with annular fins under free convection at different inclination.

This study demonstrates the effect of different mass flow on the condenser heat transfer coefficient with annular fins under natural convection at different inclinations. In this study annular fins are used for the experimental work dimensions of which are length of fin, thickness and spacing of fin 10mm, 1mm and 6mm respectively. The main aim of present study was to discover at what inclination angles give maximum heat transfer coefficient. The heat transfer coefficient on the external surface of heat pipe condenser section was determined by experimental method and then predicted by empirical correlations. The results obtained from experimental and Churchill and Chu for laminar were in fair agreement with not more than 22% deviation. It was elucidated the maximum heat transfer coefficient of 31.2 W/m<sup>2</sup>-K at 25° tilt angle and minimal condenser heat transfer coefficient of 26.4 W/m<sup>2</sup>-K was seen at 45° tilt angle and 200 ml/min mass flow rate. It has concluded, that mass flow rate is linearly proportional to heat transfer coefficient. Inclination angle also effect the thermal performance of heat pipe. Beyond 25° inclination heat transport rate starts decreases due to may be poor driven buoyancy force.

**Keywords:** Heat pipe, Annular fins, Free convection, Condenser heat transfer coefficient, Tilt angle

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## NOMENCLATURE

$A$	Cross-section area, $m^2$
$d$	Diameter, m
$g$	Acceleration due to gravity, $m/s^2$
$Gr$	Grashof number
$h$	Heat transfer coefficient, $W/m^2-K$
$k$	Thermal conductivity, $W/m-K$
$K$	Wick structure permeability
$L$	Length, m
$Nu$	Nusselt number
$r$	Radius, m
$Ra$	Rayleigh number
$t$	Thickness, m
$T$	Temperature, $^{\circ}C$
$\Delta T$	Temperature gradient, $^{\circ}C$
$Q$	Heat Input, W
$R1$	Fin base radius, mm
$R2$	Fin tip radius
$l$	Length of fin
$S$	Spacing between two fins
$H$	Height of condenser length
$N$	Number of fins

## SUBSCRIPTS

a	Ambient temperature
f	Film temperature
c	Condenser
e	Evaporator
i	Inner
o	Outer
w	Wall
v	Vapour
s	Solid
t	Transported

## CHAPTER 1

### INTRODUCTION

---

#### 1.1 Introduction to the thesis

In this scenario, cooling of engineering equipment's was major assignment in today engineering research. When we work on engineering equipment's as well as electronic components that outcome in creation of heat that could result in system failure due to excessive heating. Thus there is serious need of loftier heat transfer element with increasingly smaller weight, volume and cost. There are numerous systems like refrigerators and transformers that require urgent dissipation of heat for their optimum operation with advancement in machinery, the demand for heat carrying machinery has also spurred up. To overcome these type of limitations, Heat pipe is one of the novel solution to achieve the desired rate heat dissipation.

Heat pipe is a very efficient yielding heat transport appliances for distribution of heat at high rate over significant distance with minimum temperature fall. It is flexible, simple in forming and facile to be control. Of the numerous different type of system, which transport heat, but heat pipe is widely used apparatus to transfer heat from one system to another system. The main distinction between traditional equipment of heat transfer and heat pipe apparatus is it give maximum amount of heat be transferred with very small area and across significant distance without any need of external source give to the system. Moreover, prototype and fabrication is very simple because no any rotating part there, small temperature drops, and tendency to curb and transfer high heat rate at different levels these all are important feature of heat pipe [1].

In the conventional heat transport units of the 1880s like Perkin's boiler, in this boiler very simple mechanism is used to fetch a heat from one place to another place. Perkin's boiler was design in such a way in which liquid was heated with the help of hot gasses placed above the pipe in which liquid flow. In Perkins tube, heat transfer can be attain with the aid of change of phase [2]. The Perkins tube design was very close to the existence heat pipe appliance. The heat pipe was first introduced by Gaugler's and also recommended the use of a capillary structure wick [3]. After that, in early 1960s, Grover and his team partners was revel that the productivity of heat pipe was very high as compared to other traditional heat transport device and most economical heat transfer system today [4].

Heat pipe mainly consists of the three section first is evaporator section, second is adiabatic section, and third one is condenser section. There are three regions separated as wall region, wick region and vapor region. The working fluid is supposed to be vapor phase in vapor region and liquid phase in wick region. With the help of thermal input at evaporator section vaporizes the working fluid and after vaporization vapor goes towards the condenser part, after that it discharge heat from system to surrounding with the aid of natural or forced convection. Therefore condense the vapour into fluid. In the end wick structure is responsible to goes back the liquid in evaporator by means of capillary driven force action in wick.

Heat pipe also termed as superconductor of heat. The heat pipe has ability to lift up heat transfer with minimal heat loss. Thermosyphon is almost same as compared to heat pipe in many ways. But the main dissimilarity between heat pipe and thermosyphon is, heat pipe work against gravitational forces but on the other hand, thermosyphon cannot because due to lack of wick structure. The main goal of wick structure is to help condense liquid goes back in evaporator part with the help of capillary force but in the case of thermosyphon wick structure is absent. So, that's why if we design a heat pipe it should main focused about substance which are used to make a container as well as wick and also attention about which type of working fluid was used in heat pipe. These three crucial guideline was also should be kept in mind while fabrication a heat pipe. These parameters also determined on the basis of their demand and other concord criteria [1]. Figure 1.1 depict the schematic of a traditional cylindrical heat pipe. A diagram represent that heat is added at the evaporator section is labelled in red color and heat rejected at the condenser section is labelled in blue colour.

In this plot, cooling of engineering equipment demand was increase day by day due to elevation in machinery. It observed that if we want any engineering equipment can perform smoothly that is must to avoid overheating otherwise device can be damaged in little time. So, it can be done by cooling. Cooling rise up the life of equipment and increase the efficiency of component consequential was envisages by [5-8]. To overcome this problem and to achieve desire rate of dissipation as when fins are utilizing. The heat fritter away from system to surrounding can be acquire with the help of free convection or forced convection and radiation.

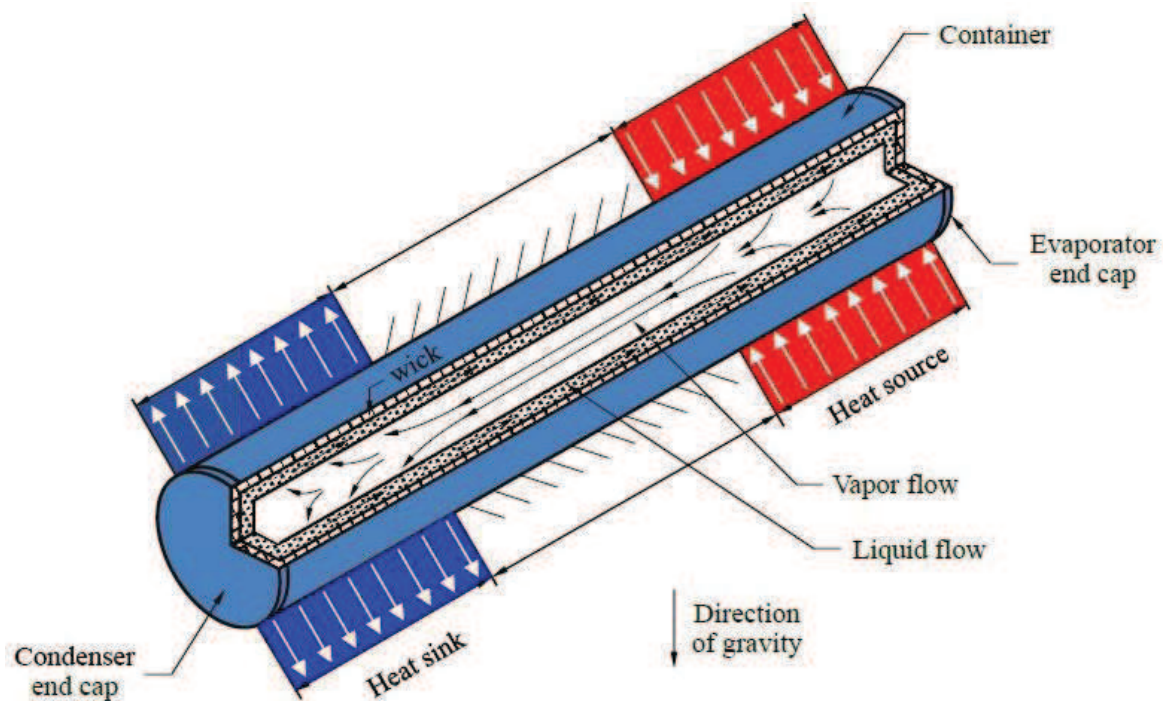


Figure 1.1: Schematic of a conventional heat pipe [1]

Heat exchange energy only between system and surrounding if temperature difference exist between them. There are three modes of transport a heat are as following:-

- I. Free or forced convection
- II. Conduction
- III. Radiation

Heat transfer by convection from one part of fluid to another part by actual motion of the molecules of the fluid is known as convection. It takes place in liquids medium as well as gases medium. Heat transfer in convection depends upon velocity of fluid. The cooling of hot fluid is rapidly if temperature is higher as compared to the surrounding. On the other hand, if little bit temperature difference between hot fluid and surrounding then cooling rate takes place slowly. According to Newton, the rate of body which loses heat is totally depend upon temperature difference between the bulk body and surrounding and formula is expressed in are as follow:-

$$Q = h A_s (T_s - T_a)$$

Where,  $h$  = Coefficient of heat transfer convection

$T_s$  = Temperature of hot counter

$T_a$  = Temperature of ambient

$A_s$  = Area of surface

Heat transfer of convection can be increase by three ways are as follow: -

- I) firstly, heat transfer increase with increase temperature distinction between area of surface which are in contact and fluid which are move.
- II) Secondly, heat transfer also increase by increasing the velocity of air above the body with the help of external source.
- III) Thirdly, expand the surface area of contact with the help of fins.

Mostly to control the temperature between system and surrounding is not optimum and enhancing the heat transport rate with the help of external source such as pump, fan etc. lead to the cost. So demand is that type of device which increase the heat transfer rate and no more effect on cost and maintenance. Fins (extended surface) fulfill all types of requirements.

The use of fins is more suitable, concern free and cheap way to increase the heat transport rate. In today most of the engineering component used fins by fabricate fins above the surface in which fluid flow to obtain desirable amount of heat transfer. However, it also should be kept in mind if we add more and more number of fins to increase the area of contact surface that doing area of surface increase but heat transfer rate start decreasing because in between fins formation of boundary layer does not fully developed [9-12].

#### **TYPES OF FINS: -**

- a) Straight fins
- b) Annular fins
- c) Pin fins

An annular fin is widely used to increase the heat transfer rate. Annular fins varies radially the addition of fins on the surface area in contact with the fluid is move, spurred the convection current with the increase of convection current heat transfer also increases. There are numerous example of annular fins is used on heat pipe, cooling electronic components and on huge varieties of heat exchanger. Mostly, used configurations are circumferential fins with triangular, rectangular and hyperbolic profile.

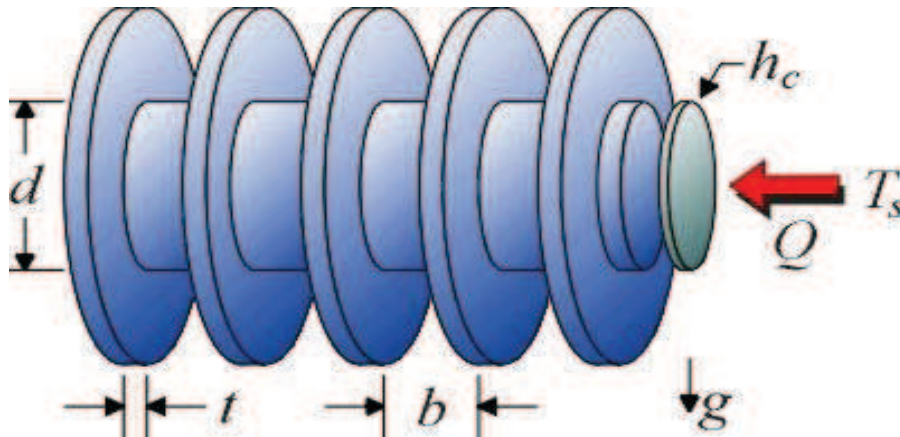


Figure 1.2. Schematic of annular fins of uniform thickness

### 1.2 Scope of work

In engineering field, demand of heat pipe increasing day by day because it has good property to transfer a heat at desired rate. Hence a straight copper water heat pipe is be used in my research, and also used annular fins over condenser section under natural convection, so only the heat load under 100W would be consider.

In the last few days, needs of increasing heat transfer rate has play a vital role in electronic device such as computer, laptops etc. because the consumption of power of electronic device is twice every 15 month but volume remain same so leads to system failure. Fins are the best way to enhance the heat transfer and prevent the system for overheating. Annular fin is one of the best choice for me because it is simple in design and reliable.

By study the history of heat pipe as well as fins that I congregate from my research work, I could be adequate to recommend the orientation has greatly impact on copper water heat pipe be used give foremost result with annular fins under natural convection. It would also be accepted through this study with the addition of fins over condenser section under natural convection at different inclination is enhance the heat transfer rate of heat pipe with fins or not. After that study the previous history I will approach this result, the heat pipe with annular fins is best way to approach desired rate of heat transfer in fortune to solve the heat waste related problem inside an engineering components.

## CHAPTER 2

### LITERATURE REVIEW

---

#### 2.1 Fabrication of a heat pipe

The main three basic parts of heat pipe is a container, a wick structure and a working fluid. In the inner part of heat pipe wick structure settle down and main function of wick structure is to give the capillary driven force for the liquid goes back condenser to evaporator [13]. Three basis section in a heat pipe are shown in the Figure 2.1

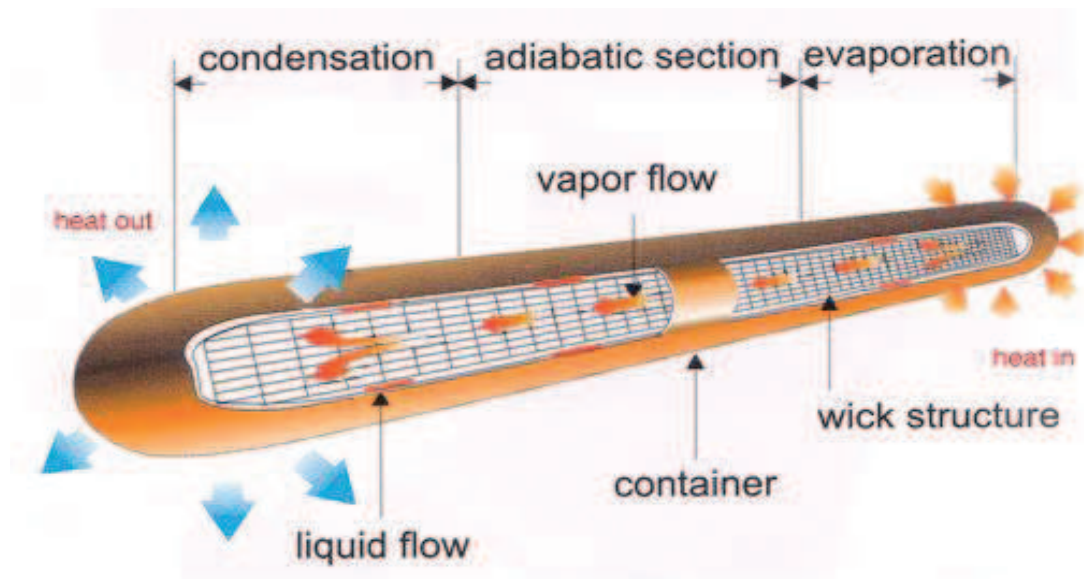


Figure 2.1: Schematic diagram of heat pipe [13]

##### 2.1.1 Selection of working fluid

Working fluid is also one crucial element for proper heat pipe operation. Here some important property should always be kept in mind for selection a working fluid inside heat pipe. Generally, working fluid is stipulate on the behavior of cost of working fluid, easily available, high compatibility with container and wicks material which are wick made. Moreover, the working fluid with high thermal stability, surface tension at the enumerate temperature and pressure. It also has high latent heat and thermal conductivity.

For low temperature range up to  $30^{\circ}\text{C}$  to  $200^{\circ}\text{C}$  water best heat transfer rate property as compare to other working fluid which lie in this range such as ethanol, ammonia, mercury, pentane, toluene etc. an easily available. I also operate heat pipe in between range so we considered, distilled

water is best for using working fluid because it cheaper and easily available. The heat pipe neither in completely filled nor be over filled because over filled may block condenser and incompletely filled may reduce the performance of heat pipe. Working fluid can be chosen from Table 2.1.

Table 2.1. Selection of working fluid [14]

Medium	Melting point (°C)	Boiling point (°C)	Useful range (°C)
Pentane	-130	28	-20 to 120
Methanol	-98	64	10 to 130
Ammonia	-78	-33	-60 to 100
Ethanol	-112	78	0 to 130
Silver	960	2212	1800 to 2300
Mercury	-39	361	250 to 650
Acetone	-95	57	0 to 120
Water	0	100	30 to 200
Toluene	-95	110	50 to 200
Heptane	-90	98	0 to 150
Lithium	179	1340	1000 to 1800

### 2.1.2. Selection of heat pipe container

The heat pipe is a made of blanks sealed hollow container which consists of all three compulsory section- evaporator, adiabatic and condenser. The selection of container must be depending on its compatibility with working fluid, high thermal conductivity and ease of fabrication. The container would be selected on the basis strength of container should be high and weight ratio because extended surface is provided at the end of the container to increase the heat transfer [1]. Humiliation of container or wick structure and also sedimentation of the working fluid in the case of Nano fluids can greatly impact on the performance of heat pipe because sedimentation of fluids lead the chemical reaction as a result degradation of container occur. Contamination of working fluid can deposit at the end of condenser as the result decrease the condenser area. This reduce capacity of heat pipe to transport heat from system to surrounding.

### 2.1.3. Selection of wick

The wick provides a mean flow liquid goes back from condenser to evaporator section of any type of heat pipe. While very small pores are also essential at the liquid interface to provide high capillary driven force pressure. Heat pipe wick structure can be broadly classified into two categories- homogenous wick structure and composite wick structure. Homogenous wick is consisting of a single material. The main advantage of homogenous wick is simple in design, manufacture and installation. Wrapped wire screen is commonly example of homogenous wick structure. On the other hand, composite wick has significantly increase the capillary limit of heat pipe but disadvantage is high manufacturing costs. Screen covered grooves are most common example of common wick. Different wick structure has different capillary limit which play a significant role in carry a fluid from and back to evaporator [1, 15]. Several research has been done to find out the behavior of different type of wicks.

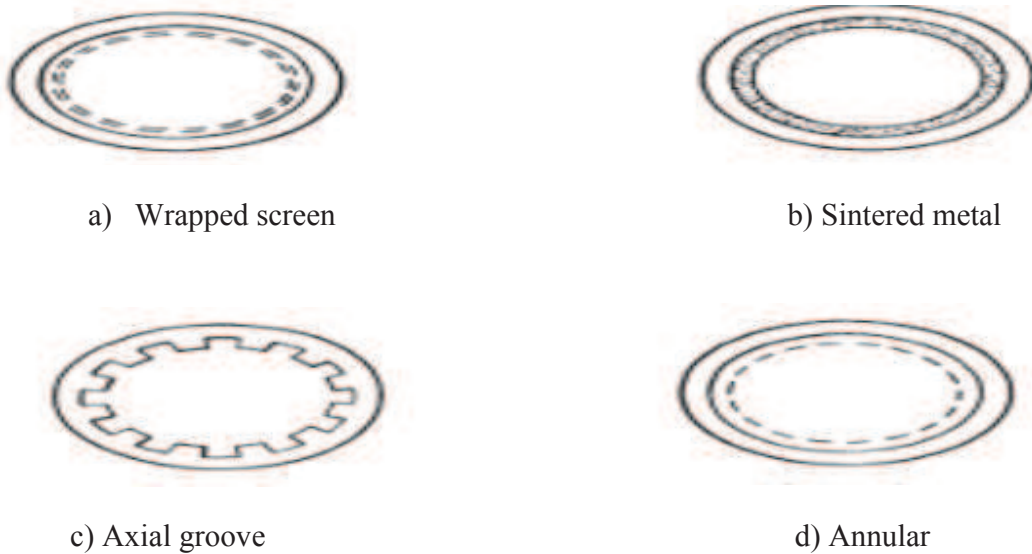


Fig. 2.2 Cross sections of homogenous wick structures [16]

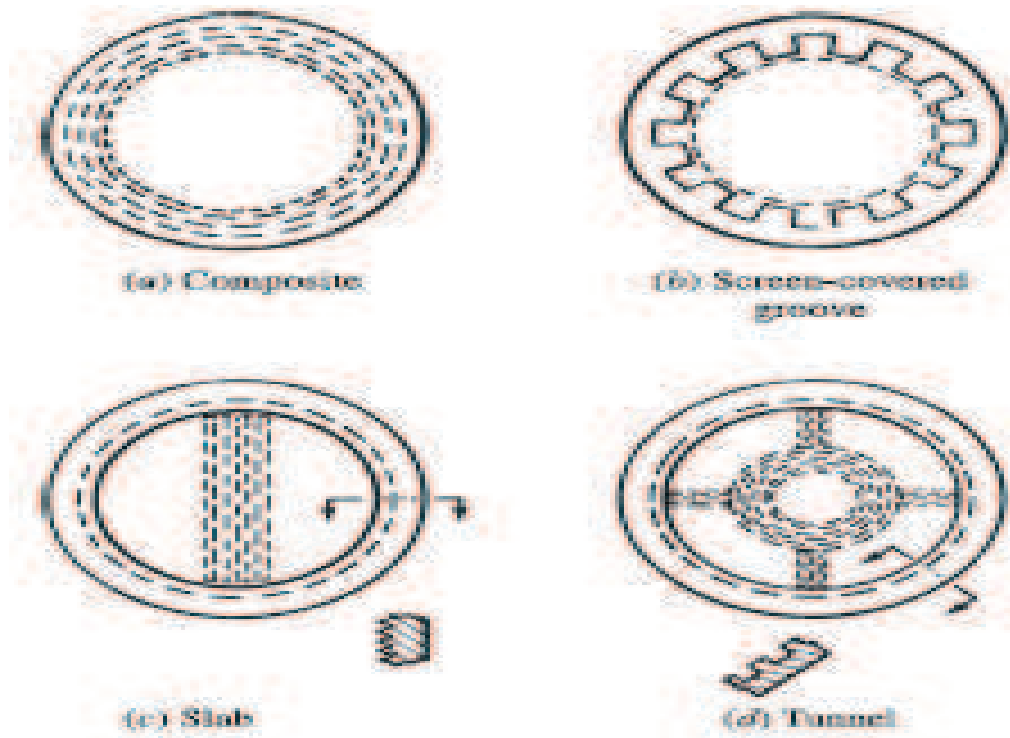


Fig. 2.3 Cross sections of composite wick structures [17]

## 2.2 Fundamental working principal of heat pipe

Heat pipe is one of the excellent transmitting device with the aid of latent heat of vaporization. The axial length of heat pipe is divide into three sections; first is evaporator section, second condenser section, and third one is condenser section. At the one end of evaporator section, heat is added externally which is connect through the heat pipe as well as wick structure, vaporize the working fluid. At the time of vaporization, the specific volume of water tube rises up nearly about 1500 time. As a result, local pressure also increases in the evaporator region. With the aid of increase pressure drive the vapor through the adiabatic section to the condenser section. Condensation will occur only, if the temperature of condenser surface is low as compared to saturation temperature of vapor. Wick structure provide the capillary force as a result, liquid return back condenser to evaporator section. Heat pipe is also known as closed two-phase cycle because during operation first liquid flow from evaporator to condenser and after that return back condenser to evaporator. Block diagram depict the working principal of heat pipe as shown in Figure 2.4. It

is also capable to transfer a heat energy near about hundred times more than to the solid metallic conductors of same physical dimensions.

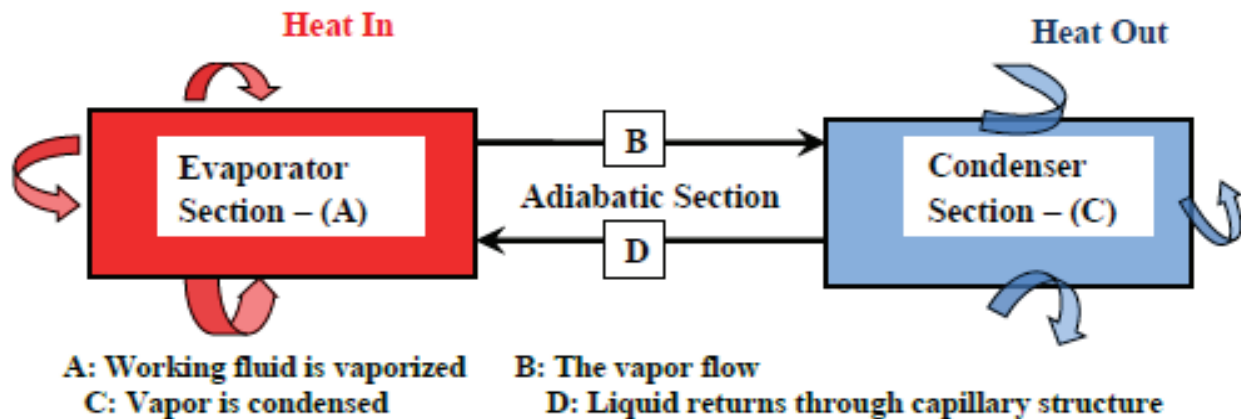


Figure 2.4 working of heat pipe [18]

### 2.3 Types of heat pipes

There are several type of heat pipe of heat application which type of heat pipe are used depending on different application. Working principal of all heat pipe are same but only difference in configuration. Cylindrical heat pipe is mostly used in many engineering components. Some other type of are discussed as follow [14]

- Annular heat pipes
- Rotation superconductor
- Loop superconductors
- Gas-loaded heat pipes
- Oscillating heat pipes
- Pulsating superconductor
- U- tube heat pipes

### 2.4 Limitations of heat pipes

There are several heat transfer limitations occur at the time of working of heat pipe. It depends upon mainly which type of working fluid are used, wick structure materials, container materials and specification of heat pipes. Limitation can be divided into categories: failure limit and non-failure limit. Failure limit also divide into three categories: capillary limit, boiling limit and entrainment limit. Non failure limit: viscous limit, sonic limit, condenser limit. The primary

limitation in using any type of heat pipe are depict in which give the imbalance between heat flux and temperature. If we want heat pipe perform well function, then heat pipe always operate below the dome region. It also should be kept in mind the maximum capillary pumping pressure ( $\Delta P_{c,max}$ ) is always be greater as compared to the total pressure fall in the interior of heat pipe. The pressure fall consist of mainly three components are discussed as follow: -

- The pressure drop ( $\Delta P_l$ ), to carry the liquid from condenser section to evaporator section.
- The pressure drop ( $\Delta P_v$ ), compulsory to move the vapor from evaporator to condenser.
- The pressure drop ( $\Delta P_g$ ), should be negative, positive and zero because it depends upon gravity. It mainly depend on location of heat pipe.

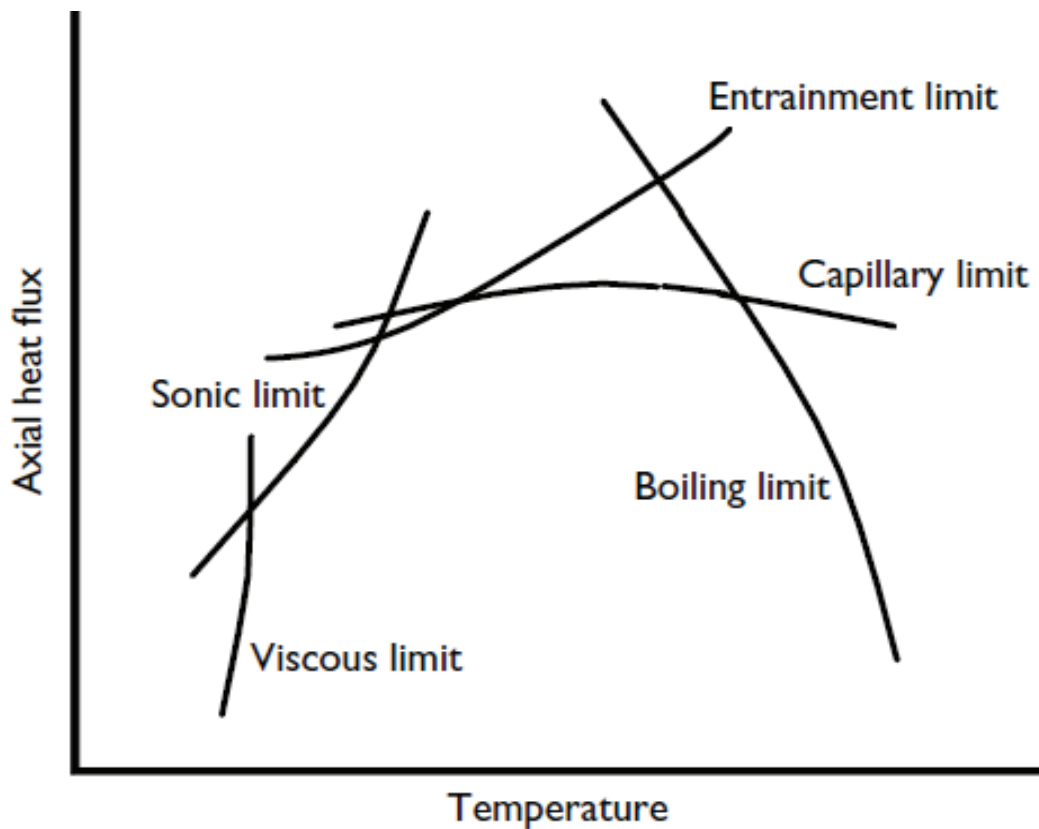


Figure 2.5 Limitations to heat transfer in a heat pipe [14]

For optimum operation of heat pipe [14]

$$\Delta P_{c,max} \geq \Delta P_l + \Delta P_v + \Delta P_g \quad (2.1)$$

Otherwise, if this equation (2.1) is not satisfied the heat pipe will not work accurately. So it should always remember while design a heat pipe.

## **2.5 Application of heat pipes**

Heat pipe have a wide range of applications. They can be used for cooling transformer, I.C engines, mobile phones, light water nuclear reactor etc. Due to rapid industrialization, has highly increase the demand of heat pipe [19-21]. By its own nature, heat pipe always works at uniform temperature as a result to keep away from irregular temperature across over a body. Mostly, all newly developed computers and laptops are employed heat pipe inside because to avoid the damage of equipment and also to enhancing the heat transfer rate. In traditional technology computers are used a finned heat sinks in line associated with the microprocessor for cooling always needed an external source such as fan to remove undesired heat into the system. But later on the introduction of heat pipe almost vanish the need of fans it can operate under free convection. Eliminate the need of a fan in computer also reduce the noise and space. Moreover, to achieve a high heat transfer coefficient on the condenser side of heat pipe, a forced convection mechanism can be used. In modern era, high heat load can easily be handed with the aid of heat pipe.

## **2.6 Selection of fins**

Extended surface or fins are used to increases the heat transfer due to increase surface area of cross section in which convection process occur. The fin material should have high thermal conductivity and minimize temperature variation from base to top. There are many type of fin including Pin fin, Straight fin, annular fin etc. The previous literature suggests under natural convection the use of three or four fin per inches [22]. Several considerations should have kept in mind while design and selection of fins: -

- Thermal conductivity of fin material should be high. Aluminum material is widely used for fabrication of fins because of it low weight and cost, and it resist to corrosion.
- It also depends of spacing for horizontal cylinder spacing will be lies between 5 to 6 mm and vertical cylinder spacing will be lie between 7 to 7.7 mm [26, 27].

### 2.6.1 Proper length of fin

Length of fin is also one important parameter of fin. We know that the length of fin is directly proportional to the heat transfer rate. However, temperature drop along the fin follow exponentially path so that's why it reaches the surrounding temperature at some length. After beyond this length it does not contribute any heat transfer. Therefore, design extra-long fin is meaningless as a result wastage of material, increase size and excessive weight and also cost increases [23]. Figure 2.6 depicts the schematic diagram of proper length.

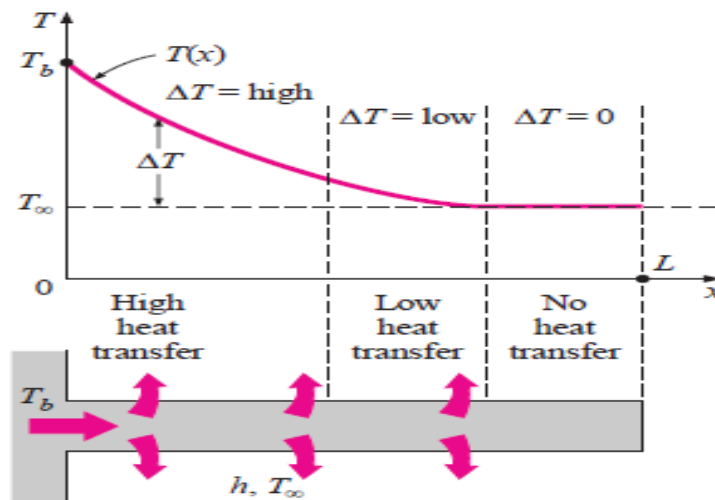


Figure 2.6 Schematic diagram of proper length of fin [23]

### 2.7 Applications of fins

Common application of finned surface is as discussed below: -

1. Cool down the temperature of electronic components
2. Condensers and economizers
3. Dry type cooling towers
4. Compressors of air cooled cylinder, IC engines
5. Electric motors and transformers

### 2.8 Previous research work in heat pipe and fins

**Nagarani et al.** [24] presented the study of how fin with heat exchangers be cast-off preceding two decades in the sector of heat transfer problems. Due to the advancement of technology, demand of such type of device is rises up which performance is efficient, light in weight as well as cheaper. The author was investigated five major type of fins are as: circumferential fins, clipped

fins and clipped tube, pin fins, longitudinal fins by experimental as well as analytical method. The researcher was observed after study the previous literature of extended surface are as below:-

- I) Coating on fin play a vital role to enhance the heat transfer coefficient because if we coating properly over the surface which fins are placed more and more air molecule get in contact with surface.
- II) The author also found that clipped fins have a higher heat transport rate as comparisons with circumferential fins along with eccentric fins.

**Kang** [25] investigated the optimum fin height of circumferential fins which are in rectangular shape. In this research author was used variable separation method used to calculate the height of fins. According to the results observed by author, the extreme loss of heat, minimal fin resist, and maximum effectiveness is directly proportional to the interior fluent convection characteristic number, optimum height of fin, and thickness of fin base along with surrounding convection characteristics number and also observed that optimum length of fin is always lies between 1.70mm to 10.6mm. Lastly, optimum fin of length reduce directly with the spurred up of the base thickness.

**Senapati et al.** [26] did an investigation of free convection rate of heat transfer when a cylinder in vertical position along with circumferential fin. In this paper, the researcher conduct numerical investigation by fluctuate Rayleigh number in laminar flow as well as turbulent flow. His calculation was fetch out by changing spacing of fin to diameter proportion ( $S/d$ ) and fin to tube diameter proportion ( $D/d$ ) lies in the scale of 0.126-5.84 mm and 2-5 respectively. After numerical investigation of author observed that are as following:-

- 1) Up to some number of fins added over the cylindrical surface, the heat transfer coefficient goes on increasing for both laminar as well as turbulent flow firstly the rate of heat transfer reach top value after more addition of fins the heat transfer start decreases because with the increase the number of fin proper boundary layer not formed as a result small amount of heat exchange between system and surrounding.
- 2) It also established that the maximum heat transfer takes place in the case of turbulent flow and also predicted that optimum fin spacing lies between 7 and 7.7mm

**Senapati et al.** [27] performed a numerical investigation of free convection rate of heat transfer when a cylinder location is horizontal along with circumferential fins. In this research, founder

used both Navier stoke and energy equation to calculate the numerical investigation of free convection rate of heat transfer along with circumferential fins of uniform thickness for the laminar flow in the scale of  $5 \leq Ra \leq 10^8$ . After the result, the author observed that the ideal spacing of fin for extreme rate of heat transfer lies in the middle of 5 to 6 mm for Ra in the domain of  $5 \leq Ra \leq 10^8$ . It also established the correlation for optimal spacing of fin is linearly depend upon Ra and D/d which can be very helpful to industrial purpose.

**Baidya et al.** [28] is carried out their investigation of annular fins to learning the heat transfer characteristic under forced convection. He took three variants of fins first, with 11mm diameter without annular fin second, fin are used for research having 31mm diameter and last one is circumferential fin having 31mm diameter subjected to be forced convection at distinct power along with Reynolds number. In this experiment author taken as fins made of aluminum because aluminum has high thermal conductivity. After experimental results, the author was observed it was found to be base diameter for annular fin is reduced by one- third as compared to fin with that are as below:-

- I) The temperature of base of circumferential fin is decrease near about 30% with the comparisons of annular fin having diameter 11mm. Because surface area increase roughly about 40%.
- II) It also observed that if the Reynold number is increase than heat transport rate also spurred up that mean higher Reynold number that will higher rate of heat transfer because large number of molecule come in contact those surface which surface fluid move.

**Lee et al.** [29] performed experimental investigation of free convection when cylinder placed in vertical form along with plate fins at some angle. In the present paper, author was performed for various fin number, base temperature and inclination angles. After experimental results, it give the correlation and this correlation applicable to certain specific range ( $100,000 < Ra < 600,000$ ,  $9 < N < 36$ ,  $30 < \alpha < 90$  ). The results hence gathered also proved that are as below:-

- I) It found that thermal resistance of radial plate fins is 30% higher as compared to thermal resistance of vertical cylinder with inclined fins.
- II) It also observed that plate fins with inclined position give better thermal resistance.

**Prakash et al.** [30] did an experimental envisages of the rate of heat transfer performance of V-notched and combination of V-notched and perforated fin arrays under free convection. The main aim to conduct the experiment is to find out the optimum combination of v-notch and perforation to increase the heat transfer rate under natural convection. Results demonstrate that due to combination of V-notch and perforating both surface area and also turbulence rise up as a result fresher air come in contact with fin and vigorously effect the heat transfer. In the nut shell, perforation help to increases turbulence as well as dissipation rate.

**Yildiz et al.** [31] conduct experiment to learn the performance of circumferential fins when cylinder placed on a horizontal position under free convection rate of heat transfer. He took of 18 pairs of circumferential fins climb up on a cylinder when placed in horizontal location having 24.9mm diameter and constant thickness 1mm, diameter of fin is varied 35mm to 125mm and fin spacing is diverse from 3.6mm to 31.7mm. His investigation revealed that the rate of heat transfer by convection process of circumferential fins is mainly depends upon specification of fins such as fin diameter, fin spacing and temperature difference between base and ambient.

**Singh et al.** [32] studied the performance of heat transfer of fin is investigated with many extensions such as trapezoidal extension, rectangular extension, triangular extension and circular segmental extensions. In this research was to do a comparison test between the heat transfer of fin with same geometry having numerous extension and without extension. Researcher analysis the fin performance with the help of software Auto desk simulation multi-physics. After analysis he observed that heat transfer through fin with rectangular extension is high as compared to other type of extensions. It also observed that fins with extensions to increase heat transfer near about 5 to 13% as compared to fin without extensions, effectiveness of rectangular fins is also high as compared to other type of extensions.

**Faghri** [33] detailed about that the heat pipe included history background of heat pipe, principle of operations, properties of heat pipe, cons of superconductors, types of superconductors and numerous application of superconductors. In many numerous previous decades, numerous element has been decided to a major metamorphosis in the field of heat pipe. Heat pipe plays a vital role to the fields of electronic and energy because all latest laptops, microprocessor use heat pipe for cooling purpose. It also suggests numerical modelling, scrutiny as well as simulation of

superconductors has been greatly impact on heat pipe performance and also understand deeply about heat pipe.

**Fadhil et al.** [34] has conducted the experimental to investigate the thermal performance of thermosyphon pipe with circumferential fins over condenser section. Thermosyphon pipes have extremely high thermal conductivity. It is manufactured from copper and DI water is used as a working fluid with filling ratio equal to 50% of the evaporator volume. Annular fins are used made up of aluminum. He studied how different input power (2W, 5W, 10W, 15W, 20W, 25W, 40W) and different inclination angle ( $30^\circ$ ,  $60^\circ$  and  $90^\circ$  from horizontal) effect the thermal performance of thermosyphon. The best results were obtained when the pipe is position at orientation angle of  $30^\circ$  as comparisons with another orientation angle. It also suggests that if we increase the input power as a result thermosyphon pipe temperature also rise up.

**Vijara et al.** [35] is carried out the experimentation to learn the thermal behaviour of concentric annular heat pipe. CAHP can be achieved high heat transfer rate as contrast to conventional heat pipe because CAHP has large area as contrast to traditional heat pipe. The main aim of the experiment to find out the performance of CAHP if we change the inclination angle and heat input. After experimentation the founder found that are as following:-

- I) It observed that, if the heat input increased as a result temperature difference between evaporator as well as condenser section start decreases for all inclination angle.
- II) It also observed that least thermal resistances were found at vertical position of CAHP.

**Goshayeshi et al.** [36] study the effect of  $\text{Fe}_2\text{O}_3$  Nano particles where added to kerosene as a working fluid under magnetic field on the performance copper oscillating heat pipe. Author conduct experiment with different inclination angles. The main aim of researcher in this paper to find the temperature distribution of oscillating superconductor as well as transfer rate of heat of OHP. It observed that after experiment with addition of  $\text{Fe}_2\text{O}_3$  Nano particles under magnetic field increase the thermal performance of OHP mainly in  $75^\circ\text{C}$ . Magnetic Nano fluid  $\text{Fe}_2\text{O}_3$  can also decrease thermal resistance as compare to kerosene.

**Nemec et al.** [37] is studied the behavior of heat pipes with wick. The ideal working position of heat pipe investigated. It operated on maximum mass flow transfer and maximum performance at what position. In this experimental work the author found that at what positions such as horizontal location as well as vertical location wick heat pipe give better performance. After experiment

conduct, Author found that wick heat pipe was can be operate at horizontal location and it also conclude that overall heat transfer is not much distinct as contrast with vertical position. Because capillary action is almost same.

**Yadav et al.** [38] studied the review of fins on heat transfer. In today, mostly electronic component release heat during operation which must be transferred to the environment properly. Otherwise equipment will damage. The main goal of extended surface to limit the maximum temperature. Mostly, extended surface is made of aluminum because of it high thermal conductivity. The heat transfers also depend on the parameter of fins such as length, thickness, spacing, no of fins, inclination of fins, cross sectional area and temperature difference between fins and surrounding. It also suggests that the efficiency and best heat transfer rate of the exponential profile is higher in the case of rectangular profile.

**Kumar et al.** [39] investigate the heat transfer of heat pipe by comparing experimental data and analytical model. In this research, forced convection process is used at the one end of evaporator portion of wire screen superconductor and condenser portion with circumferential fins under free convection is used. In this paper analytical model was establish on the basis of thermal network resistance approach. This model determines thermal resistance at the outer surface of the evaporator as well as condenser. The main goal of experiment to find out the thermal behavior of heat pipe. It also studies the effect of many operating parameters such as heat pipe inclination angle as well as heating fluid temperature of evaporator where investigated by experimental. The experiment result compare with analytical model for the validation. It found that the heat transfer coefficient determined by predicted model a wire screen superconductor was found that is acceptable when compared with experimental results. It also concludes that maximal heat transfer rate of heat pipe was found at inclination angle of  $25^\circ$  and  $70^\circ$  C temperature of heated fluid.

**Senthil kumar et al.** [40] is conducted experiment to learn the performance of heat pipe with aqueous solution of n-pentanol at varying inclination. The main intention of research to differentiation between heat pipes employed with n-pentanol and heat pipe employed as well as water at distinct orientation. The experiment result hence obtains from this research are as follow:-

- I) It observed that heat pipe employed with n-pentanol give better performance of heat pipe as contrast heat pipe employed with water.

- II) Generally, water is commonly used as working fluid because it is cheaper and easily available at all places. But water has some cons if we used as working fluid.
- III) The main pros of n-pentanol if we used as a working fluid because it provide very high boiling limit and capillary limit. As a result, heat pipe suitable for large heat load application.

**Moraveji et al.** [41] studied the thermal behavior of superconductor (heat pipe) by using  $\text{Al}_2\text{O}_3$  nanoparticle having diameter 35 nm. He hold a heat pipe built up of Cu of distinct length and wick structure. In this research, heat pipe is used there  $90^\circ$  curve between evaporator and condenser section. Experiment conduct with concentration of Nano fluid 0%, 1%, 3% by weight. He compares the result with pure water and found that are as following:-

- 1) It noticed that temperature of wall rise up with the increases of heat load at evaporator side.
- 2) It observed that if heat pipe used with  $\text{Al}_2\text{O}_3$  nanoparticle as a working medium temperature of wall surface reduced with the comparisons of pure water as a working medium.
- 3) It also observed that resistance of water heat pipe was more as contrast to thermal resistance of heat pipe employed with nanoparticles.

**Kang et al.** [42] investigation the behavior of heat pipe with silver Nano fluid. The researcher used this Nano fluid as working medium for a traditional 211  $\mu\text{m}$  width and 217  $\mu\text{m}$  depth a deep grooved circular superconductors. Researcher aim is to determine the temperature distribution of DGCP as well as compare the thermal resistance of heat pipe in which silver Nano fluid are used as working fluid and on the other side DI water are used as working media. The concentration of nanoparticle was used in this test in the range of 1mg/l to 100mg/l. The condenser part of superconductor was cooled by  $40^\circ$  with the aid of water bath. After experimentation the researcher noticed that and described are as following:-

- A) Temperatures distribution of heat pipe wall was start decreases when silver Nano fluid are used as working fluid as compared to DI water are used as a working media.
- B) It also noticed that if density of nanoparticle was increase then thermal resistance start decreases.

**Mouses** [43] presented the concentration of Nano fluid was greatly impact on the behavior of circular superconductors. Founder used two type of working fluid medium one is aluminum oxide and another one is water. The main purpose of conduct experiment to find out performance of

superconductor at distinct operating condition. In this paper it also study about the effect of filling ratio, density of Nano particles and thermal resistance of superconductor. In the nut shell the author observed if the concentration of Nano particle spurred up then thermal resistance starts decreases.

**Indrus et al.** [44] carried out investigation with the help of experimentation to learn the performance of Cu heat pipe with wick. The dimension of cylindrical superconductors is 10mm external diameter as well as length is 300mm. Experiment was conducted at distinct orientation and heat input load. It suggested that behavior of any circular heat pipe was totally depend upon the temperature difference between condenser as well as evaporator region because if the temperature difference is more than thermal resistance is low but on the other if temperature difference is low then thermal resistance is high which is not good for any type of heat pipe. The author reported best result was come when heat pipe operated at angle between  $30^{\circ}$  and  $60^{\circ}$  inclination angle and heat input was between 20W to 80W.

**Noie et al.** [45] studied the thermal behavior of a thermosyphon under various inclination angle. Many experiment were conducted at varies inclination angle from  $5^{\circ}$  to  $90^{\circ}$  and filling varies from 15% to 30%. A thermosyphon was made up of copper materials having inside diameter, outside diameter and length of 14.5 mm, 16 mm and 1000 mm. respectively were used in this study. In thermosyphon working fluid medium is water. According to the experimental results, author observed that the best outcomes was come when operate at an angle between  $15^{\circ}$  to  $60^{\circ}$ . A very close result was found if author result compare with preceding literature survey.

**Teng et al.** [46] envisages with experimental how Nano fluid effect the thermal behavior of heat pipe. The author used aluminum Nano fluid in this experiment. Before experiment Nano fluid was first prepared in this experiment the founder Nano fluid prepared by straight method which was prepared by direct method under 3 varying concentrations 0.5%, 1%, and 3% by weight. Several time of Nano fluid was dispersed for near about one month because after one month give good suspension also greatly impact the thermal performance of superconductors. In this experiment, the author hold a heat pipe which is manufactured by copper having inside diameter 8mm and axial length is 600mm. The main aim of researcher to conduct experiment is how density of Nano fluid and inclination angle effect the thermal behavior of heat pipe. After experimentation the author found that heat pipe work accurate when operate with 1% concentration of nanoparticles and efficiency spurred up to near about 18% as compared to base fluid.

**Kumer et al.** [47] envisaged with the aid of experimentation to learn that thermal behavior of superconductors with  $\text{Al}_2\text{O}_3$  nanoparticle as well as DI used working fluid medium. He also studied how tilt angle, filling ratio, heat input effect the heat transfer. It also conducted the experiment with different inclination angle, heat input and filling ratio. After experiment the result was obtained that, firstly thermal resistances start decreasing with the increase in orientation angle because temperature difference between evaporator and condenser section is high at this position and approach the minimum value in vertical position because temperature difference is low as goes horizontal to vertical positions. Secondly, if copper pipe operates at  $35^\circ$  inclination angle and 80% filling ratio the best results was achieved. Lastly, with the increase of heat input load also increasing temperature gradient along the axis of superconductor.

**Ghanbarpour et al.** [48] presented the paper if we increase as well as decrease the heat input load at the inlet of evaporator section what outcome was obtained on the behavior of heat pipe. In this research founder used a heat pipe which is built up of copper and specification of Cu heat pipe is outer diameter is 6.35 mm along with axial length is 200 mm. Aluminum nanoparticle are used as a working medium inside a superconductor. Congregation of aluminum nanoparticle was used in this research is 5% as well as 10%. This result show that 5% by weight concentration of heat pipe perform well with variable heat input as compare to 10% concentration by weight.

**Rao et al.** [49] investigated the performance of free and forced convection heat transfer from rectangular and trapezoidal fins attached to a heated horizontal base. He took a rectangular fin of dimension  $110*50*10$  mm and trapezoidal fin of dimension  $120*30*10$  mm by aluminum 6063 alloy. It was shown through result that the heat transfer is enhanced for trapezoidal fins in forced convection. It also observed that efficiency of trapezoidal fin was increased by 7.5 % in forced convection.

**Hong-Sen et al.** [50] has been studied about a circumferential fins and divided into numerous circular section. In all circular region the rate of heat transfer along with thermal conductivity of every part was to be assumed. In this paper, a recursive formula was used to give the solution of temperature distributions and rate of heat transport coefficient on annular fin for both condition.

**Naphon et al.** [51] investigated the heat transfer coefficient and fin efficiency of circular fins. Circular fin area observed in three condition dry, partly wet, and absolutely wet surface situation.

Researcher developed analytical model to determine the temperature profile of the fin. The results obtained from mathematical model was fair agreement with other researchers.

**Kundu et al.** [52] has been presented a research paper on clipped fins with the aid of semi analytical technique. In this technique, describe a type of fin are used as well explain how volume and rate of heat transfer effect the performance of any equipment which fins are placed. Elliptical fins give better dissipation rate as compared to circumferential fin along with area resist exist on either side of fins. Elliptical fins give better performance on the comparison of eccentric circular fin if the restriction was on one side.

**Chen-Nan et al.** [53] has been analyzed a research paper of combined effect of rate of heat transfer and also mass transfer in clipped fins subjected to be all three different surface conditions. The author found that if the air humidity was spurred up as a result temperature distribution of fin was also increased. It also observed that elliptical fin efficiency is high nearly about 4% as compared to circumferential fin efficiency.

**Abdel- Rehim Zeinab** [54] will investigated the impact on overall thermal performance of extended surface such as square, circumferential, and clipped pin fins associated with different fin geometries. The authors used EGM to find the resultant impact of thermal resistance as well as pressure falls. The mathematical model was developed on the basis of dimensionless variable. The result exposed that fin profile was significantly depend on these parameters.

## **2.9 Summary and research gaps identified**

The literature review depicts that masterly amount of work has been done fundamental studies of heat pipe. It found that chosen of working fluid, container material and which type of wick structure are used and also which type of material are used to manufacture a heat pipe as well as thermal resistance all these are critical parameter, which decide the thermal efficiency of heat pipe. For low temperature application in the range of 20° to 150° C copper water heat pipe is an extremely used because it is economical and easily available at all place. Addition of nanoparticle in the working fluid can also play a vital role to enhance the thermal performance of superconductor. But one major problem if we used a nanoparticle in heat pipe as a working fluid medium caused sedimentation over condenser section as a result, decrease the overall surface area and also decrease the rate of heat transport. Moreover, in natural convection extended surface or fin are

used to increase the heat transfer rate. The spacing of fin is usually around 6 mm to 8 mm is optimum in the case of natural convection as well as 2 to 3 mm in cased forced convection [26, 27]. It has also found that mostly aluminum material is used to made a made a fins because of it high thermal conductivity and easily available.

It was found that a very little amount of work has been done on cooling of heat pipe with annular fin under natural convection at different inclination with vary mass flow rate of fluid. All these feature were high priority in deciding the aim of thesis.

### **2.10 Thesis objectives**

After reading the history of heat pipe and extended surfaces literature in many book, journals, as well as thesis were decided the following objective.

- Selection of material and fabrication of annular fins for heat pipe.
- To predict the condenser side heat transfer coefficient of copper water heat pipe at different inclinations with annular fins under natural convection.
- To compare the experimental value of condenser side heat transfer coefficient with analytical method and find out at what inclination angle to achieve maximum heat transfer coefficient.

EXPERIMENTAL SETUP AND METHODOLOGY

This chapter present the design considerations of heat pipe, annular fins and also discuss about experimental procedure. The analytical and theoretical context behind various equations used in this study are also presented in this chapter.

**3.1 Detail of copper heat pipe test rig**

In this experimental work, heat pipe used is made of copper because of its high thermal conductivity. Copper water heat pipe with 7.8 mm outer diameter, 6 mm inner diameter and length of heat pipe is 180 mm has been selected for procurement of heat pipe. A specially designed heat pipe manufacture by M/s Golden Star, Pune, India was been used. The screen mesh wick is used is made of phosphor- bronze. To control the temperature of water inside the tank with the aid of PID (proportional integral derivative) mechanism.

The pipe test rig has been fabricated in such way to carry out the experiment at different inclination angles under natural convection. Tilting mechanism is used to lift the heat pipe when it goes from horizontal to vertical position. It provide at the one end of evaporator section of heat pipe. A nut and bolt arrangement can be used to loosen and fix the heat pipe at required inclination. The evaporator, adiabatic and condenser section of copper water heat pipe a 60 mm, 55 mm and 65 mm in length respectively as shown in Figure 3.1

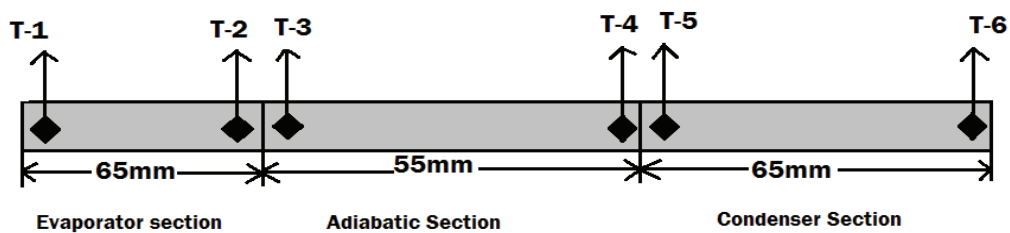


Figure 3.1: Schematic diagram of heat pipe with thermocouple position

The arrangement to change and measure the angle of inclination accurately with the help of angular protector is shown in Figure 3.2. Resistance temperature detectors are used to measure the temperature of circulating water which are calibrated before start experiment. Six RTD sensors are

placed at the surface of heat pipe at the distance of 5 mm, 55 mm, 65 mm, 110 mm, 120 mm and 175 mm respectively as shown in Figure 3.1.

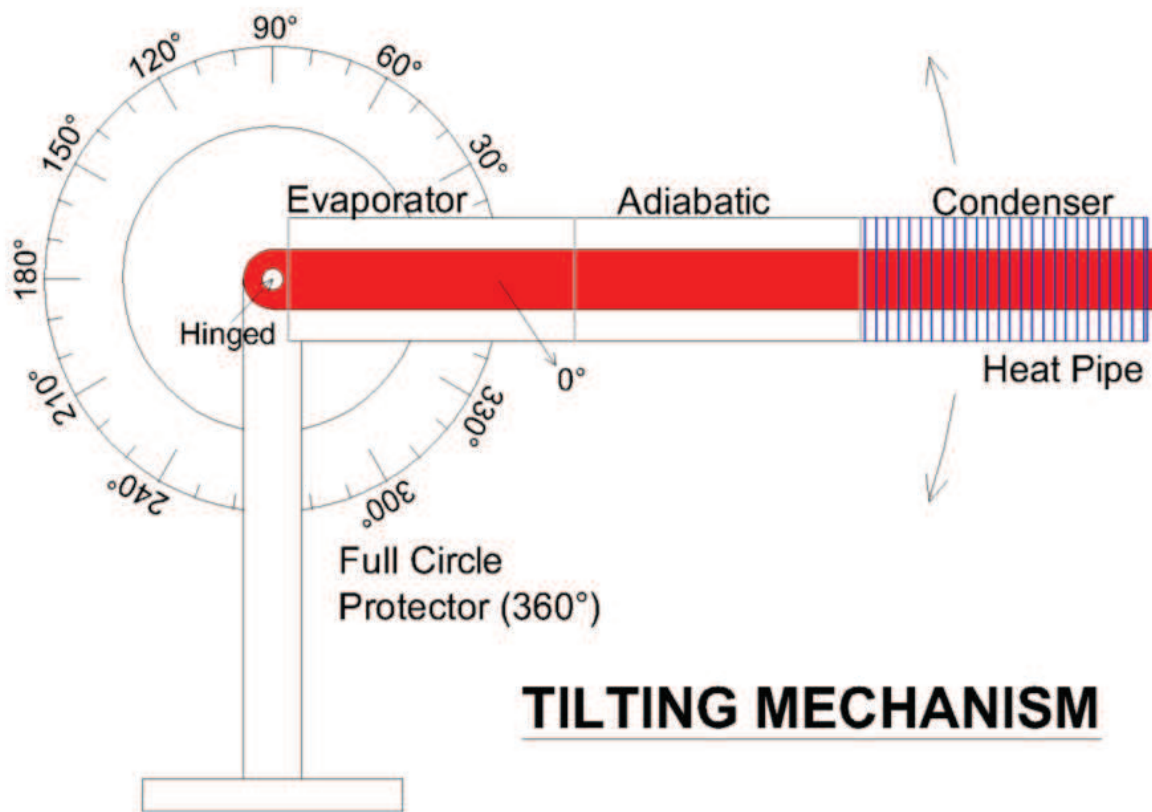


Figure 3.2 Schematic diagram of tilting mechanism

The evaporator section of heat pipe is enclosed in the form of cylindrical jacket. In cylindrical jacket heating chamber is constructed around it. The adiabatic section of copper water heat pipe is insulated with glass wool and polyurethane. The main function of adiabatic section of heat pipe is to prevent heat escape in this section so that all the heat is rejected only condenser surface. The condenser section of 65 mm axial length is cooled by fitted circumferential fins under free convection.

The rotameter and temperature sensor are used in this experimental work calibration must be done before to determine the accuracy of the instrument. Otherwise, if calibration is not done properly it always give wrong value. The schematic of heat pipes with annular fins experimental setup is shown in Figure 3.3 and Table 3.1 gives the detail of various instrument which used in the setup.

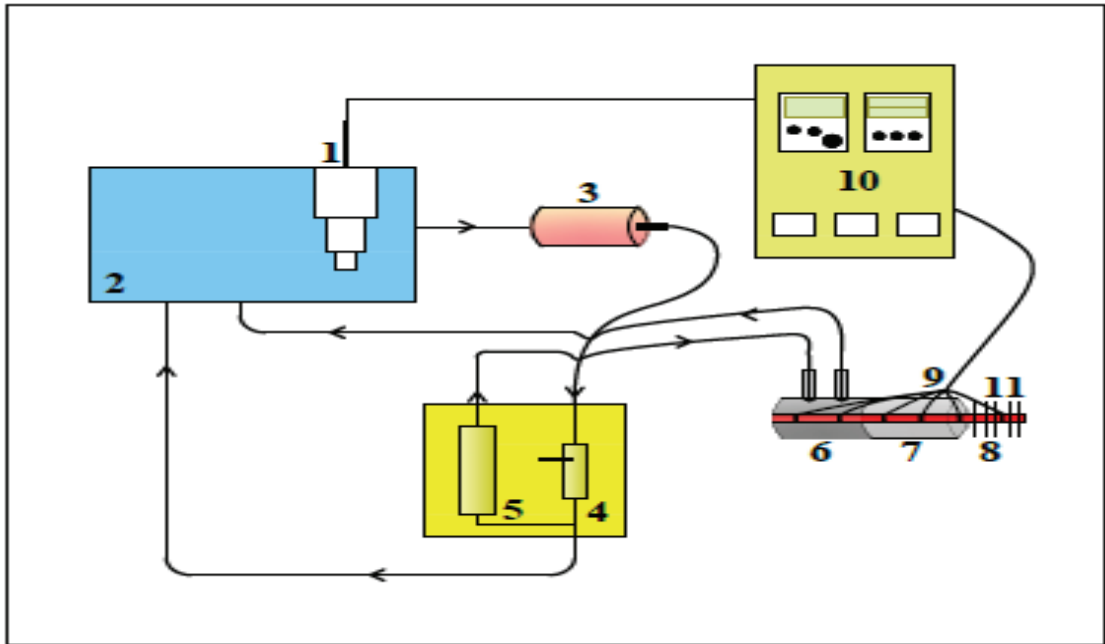


Figure 3.3 Schematic heat pipe with annular fins test rig used in this study

Table 3.1: Part description of experimental test rig

1	Heating element
2	Water tank
3	Pump
4	By-pass valve
5	Flow meter
6	Evaporator section of heat pipe
7	Adiabatic section of heat pipe
8	Condenser section of heat pipe
9	Pt-100 RTD sensors
10	Data logger
11	Annular fin

Table 3.2: Equipment details with their specifications

S.NO	Equipment	Application	Make	Specification
1.	Temperature data logger	Records and displays the temperature	i-therm AI-5441	Resolution 1 <sup>0</sup> C Accuracy 0.3% FS 90 – 270 VAC/DC
2.	Temperature sensors	Measuring heat pipe surface temperatures	Mass International	Accuracy +- 1 <sup>0</sup> C Range - 100 to +250 <sup>0</sup> C
3.	Rotameter	Flow measurement of hot water	Flowstar FSA-100	10-200 ml/min
4.	Centrifugal pump	Circulation of hot water	Vijay-50 Monobloc Pump	Head 15m Capacity 240 LPH Drive 0.05 KW 230 VAC/DC

Water is heated in the tank with the help of water heating element. The power input given to the heater in the form of temperature. Heat input can be controlled in two ways: First is by changing the temperature of circulating water and secondly by changing the mass flow rate. However, for the sake calculation the temperature value in this experiment is kept constant and only mass flow rate is varied from 40 ml/min to 200ml/min. PID mechanism is used to control the process.

Steady temperature reached after 30 to 35 min. After steady state, pump is on and hot water has been circulated from the tank towards cylindrical jacket. In this process, the water also passes through a bypass valve where the excess water is released back into the tank and remaining water is allowed to enter the rotameter to measure the flow rate. A data logger system has been used to display the temperature of heat pipe at various location on the surface of condenser as well

as evaporator inlet and outlet. The front view of fabricated heat pipe with annular fin set up used in this study as shown in Figure 3.4.

The fabrication of heat pipe experimental setup could be better understand from the top view of heat pipe with annular fins as shown in Figure 3.5. It depicts the layout of pipe from tank evaporator section. The evaporator cylindrical jacket is black in colour, adiabatic section is painted with red colour and condenser section is enclosed with annular fins under natural convection.

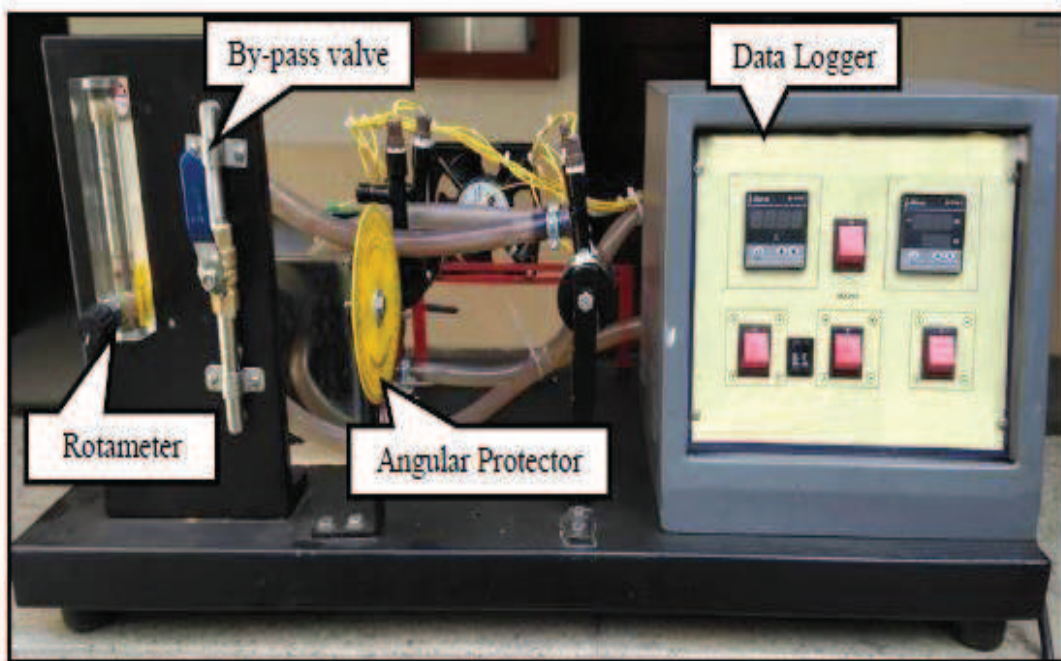


Figure 3.4: Front view of heat pipe test rig

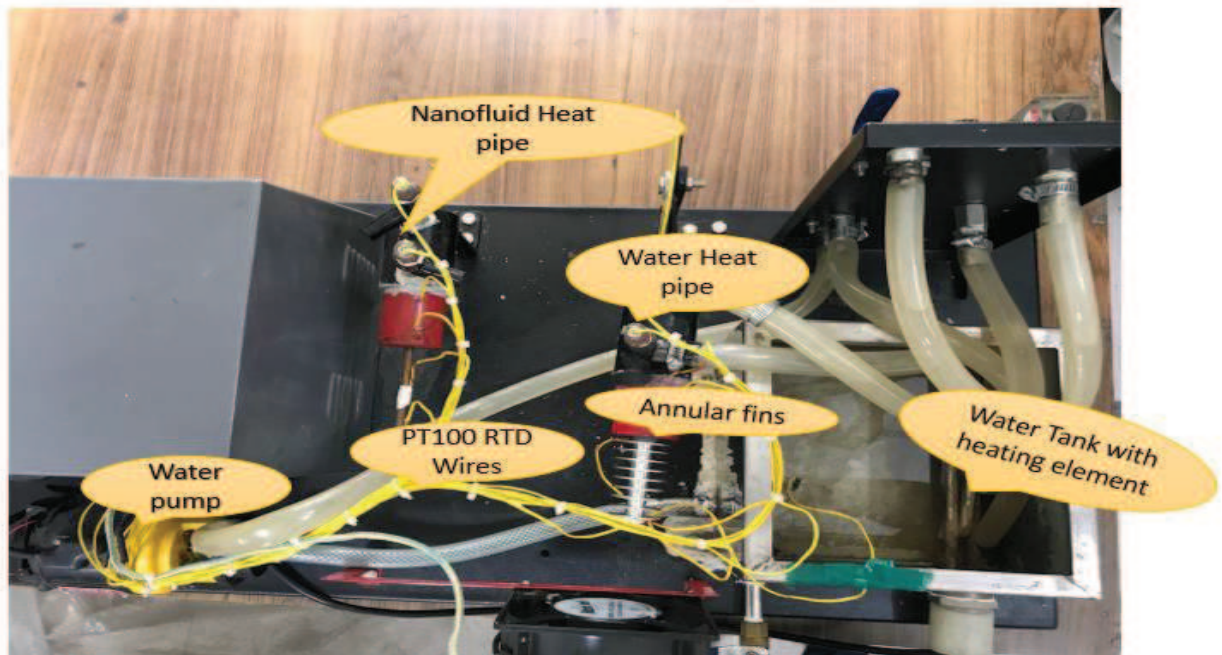


Fig 3.5 Top view of heat pipe experimental setup

### 3.1.1 Fabrication of fins

In this study, cylindrical annular fins were used which were manufactured by S.R Engineer, Industrial phase-2, Chandigarh, India. Annular fins are made up of aluminum alloys 6063. Because of its high thermal conductivity [27]. It is one of the most widely used materials for manufacture of fins and also easily available. Because it provides good resistance to corrosion and has good extrudibility and high quality surface. A6063 was alloy which is made up of two elements: one is magnesium and the other is silicon. The standard controlling composition is maintained by aluminum association. It also gives good mechanical properties and high heat transfer property. Chemical composition of A 6063 is given in Table 3.3. The 3D view of cylinder with annular fin is shown in Figure 3.6

Table 3.3 Chemical composition of A6063

Material	Si	Fe	Cu	Mn	Mg	Cr	Ti	Other
Max %	0.6	0.35	0.10	0.10	0.9	0.10	0.10	0.15
Min %	0.2	0.35	0.10	0.10	0.45	0.10	0.10	0.05

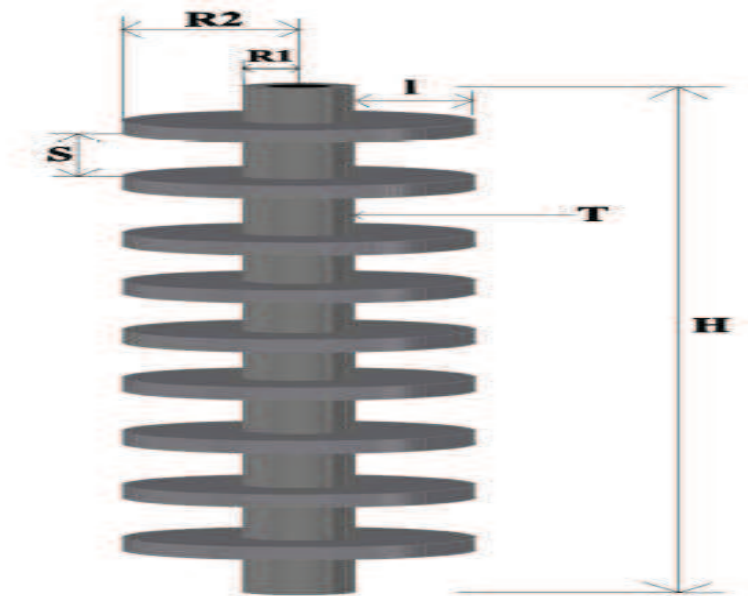


Figure 3.6 3D view of cylinder with annular fins

### 3.1.2 Specification of Fins

Various parameters on which heat transportation depends are length, spacing, number of fins and fin diameter. The optimum fin spacing for maximum heat transfer varies between 5 to 6 mm [27]. The optimum fin length is between 8 to 10 mm for natural convection [25]. Thickness of fins is also important parameter and it should be kept as small as possible to avoid conduction but in my present study fins of uniform thickness 1 mm because beyond this level it was difficult to manufactured due to mechanical constraints. Keeping this consideration in view, the condenser section of heat pipe has been provided with 9 annular aluminum fins of 32 mm diameter at a pitch of 6 mm. Specification of annular fins used in experimented are listed below is shown in Table 3.4

Table 3.4: Annular fins specification and their notation

S.no	Notation	Parameter	Value
1	R1	Fin base radius	6 mm
2	R2	Fin tip radius	16 mm
3	l	Length of fin	10 mm
4	S	Spacing between two fins	6 mm
5	H	Height of condenser length	65 mm
6	N	No of fins	9

### 3.1.3 Calibration of rotameter

Rotameter is used to measure the volumetric flow rate of fluid. For calibration of rotameter stopwatch and transparent measuring beaker was used. Calibration was done by such a way flow rate on rotameter was fixed at different mass flow rates and the water was collected in a beaker after passing through rotameter.

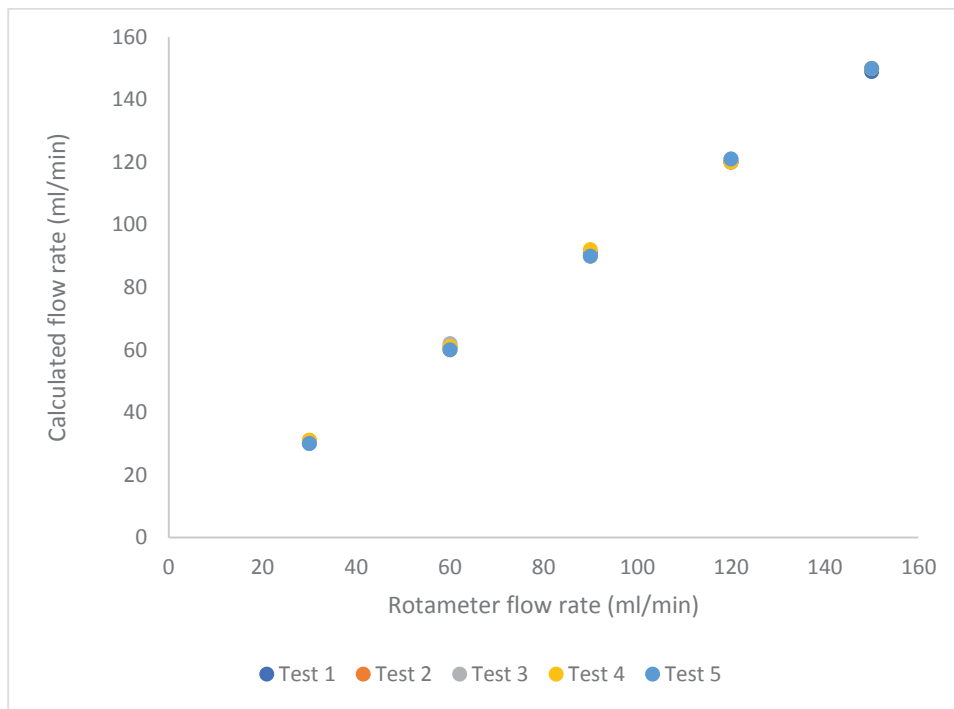


Figure 3.7: Rotameter calibration graph

The calibration was conducted in at five different flow rates, at 30 ml/min, 60 ml/min, 90 ml/min, 120 ml/min and 150 ml/min. the calibrated reading are given annexure Table A1 and calibration graph as shown in Figure 3.7.

### 3.1.4 Calibration of temperature sensor

A Six RTD sensors were placed on copper water heat pipe to display the temperature from condenser section to evaporator section of heat pipe. The RTD sensors are made up of pure materials like copper, nickel, or platinum. In this thesis work which RTD sensors are used made up of platinum. Before experiment calibration are must to perform well experiment. For this calibration water bath and standard thermometer was used.

Calibration was done by this way all the RTD sensor of heat pipe put in water bath with standard thermometer the temperature of water bath was increased step by step. Reading taken at six different temperature 20°C, 30°C, 40°C, 50°C, 60°C, 70°C and compared with standard thermometer.

At the time of calibration of temperature sensor, it was found that deviation between temperature sensor and standard thermometer were found to be within  $\pm 1^\circ\text{C}$  to  $2^\circ\text{C}$ . The calibration readings are given in annexure Tables A2 and calibration graph is shown in Figure 3.8.

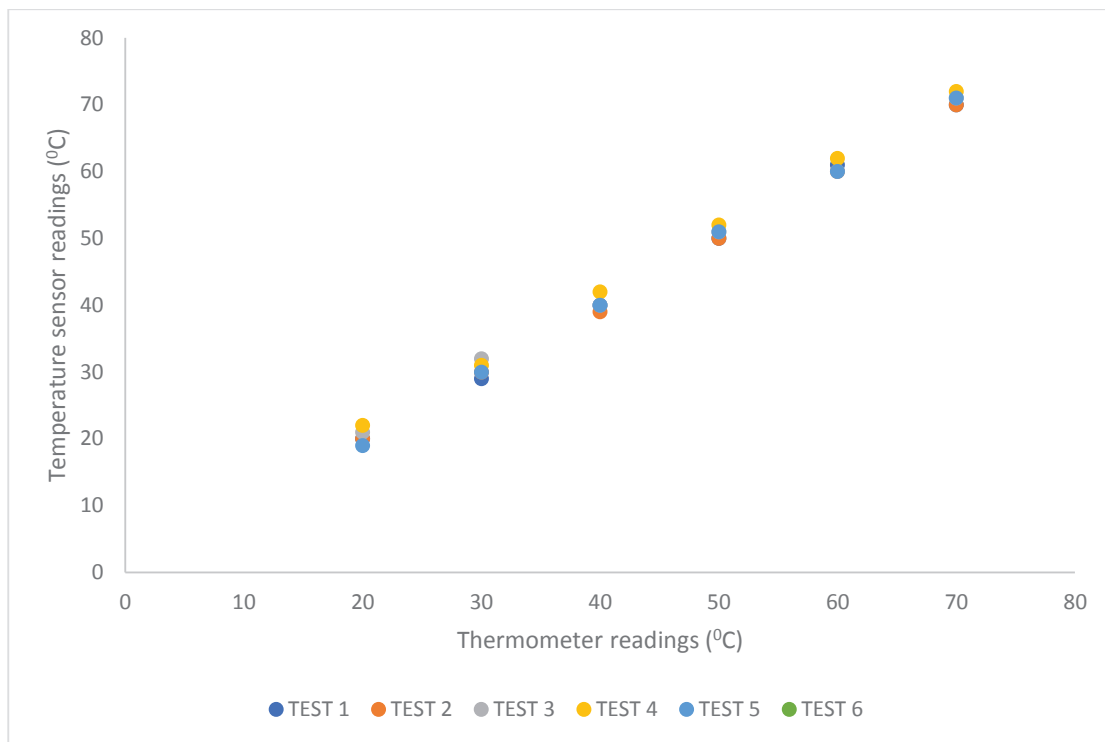


Figure 3.8: Calibration graph of temperature sensor used water heat pipe

After calibration results for both rotameter and temperature sensors, it was accepted that the device was accurate and efficient to be used for experimental work. The specifications of straight copper water heat pipe used in thesis are given in Table 3.5.

Table 3.5: Heat pipe specifications and their notation

S.NO	Notation	Parameter	Value
1.	$K_s$	Thermal conductivity of solid wick material	$50 \text{ W m}^{-1} \text{ k}^{-1}$
2.	$K_p$	Thermal conductivity of heat pipe material	$400 \text{ W m}^{-1} \text{ k}^{-1}$
3.	$A_v$	Vapor core region cross-section area	$1.9625 \times 10^{-5} \text{ m}^2$
4.	$A_w$	Wick cross-section area	$8.635 \times 10^{-6} \text{ m}^2$
5.	$T_p$	Heat pipe wall thickness	$0.9 \times 10^{-3} \text{ m}$
6.	$T_w$	Wick wire thickness	$0.0406 \times 10^{-3} \text{ m}$
7.	$K_{wick}$	Effective thermal conductivity of wick	$1 \text{ W m}^{-1} \text{ k}^{-1}$
8.	$L_e$	Evaporator section length	$60 \times 10^{-3} \text{ m}$
9.	$L_a$	Adiabatic section length	$55 \times 10^{-3} \text{ m}$
10.	$L_c$	Condenser section length	$65 \times 10^{-3} \text{ m}$
11.	$D_v$	Vapor core diameter	$5 \times 10^{-3} \text{ m}$
12.	$R_{h,v}$	Hydraulic radius of heat pipe	$2.5 \times 10^{-3} \text{ m}$
13.	$R_i$	Inside radius of heat pipe	$3 \times 10^{-3} \text{ m}$
14.	$R_o$	Outside radius of heat pipe	$3.9 \times 10^{-3} \text{ m}$

### 3.2 Experimental methodology to determine the condenser side heat transfer coefficient

In this Section, to determine the heat transfer coefficient of copper heat pipe with annular fin over condenser section under natural convection is discussed.

#### 3.2.1 Experimental procedure to find heat transfer coefficient

The following procedure is adopted for determine heat transfer coefficient:

1. Annular fin is assembled and placed over the condenser section of heat pipe with thermocouples (RTD sensors)
2. To study the performance of heat pipe under free convection number of test were conducted under steady state at a constant temperature.
3. The inclination of heat pipe from the horizontal was varied and kept at  $0^\circ$  to  $45^\circ$  tilt angle.
4. The mass flow rate of hot fluid was also varied from 40 to 200 ml/min.
5. The ambient temperature varied between the range  $32^\circ \text{ C}$  to  $34^\circ \text{ C}$ .

6. Once the steady state is achieved.
7. Note down all the required temperatures at respectively sections.
8. The heat input of the heat pipe is equal to amount of heat supplied at evaporator section and is finally obtained as shown in following equation [23]

$$Q = \dot{m}c_p(T_1-T_2) \quad (3.1)$$

Where,

$\dot{m}$  = mass flow rate of circulating fluid (kg/s)

$C_p$  = specific heat of water at particular temperature

$T_1$  = Water inlet temperature ( $^{\circ}$ C)

$T_2$  = Water outlet temperature ( $^{\circ}$ C)

9. The amount of heat dissipated by the condenser with annular fin over condenser section is equal to the heat absorbed by the circulating water in the jacket. Heat loss can be calculated by the following equation [23]

$$Q = h_cA (T_c-T_a) \quad (3.2)$$

Where,

$h_c$  = Heat transfer coefficient of condenser ( $W/m^2-K$ )

$T_c$  = Average temperature of condenser surface ( $^{\circ}$ C)

$T_a$  = Ambient temperature ( $^{\circ}$ C)

Area of fin surface can be calculated by using following equation [11].

$$A = NA_f+A_b \quad (3.3)$$

Where,

$A$  = Total surface area of fin.

$N$  = Number of fins.

$A_f$  = Surface area of each fin.

$A_b$  = Area of prime surface.

10. The condenser side heat transfer coefficient was calculated by using following equation [55].

$$\text{Heat lost} = \text{Heat gained}$$

$$h_c A (T_c - T_a) = \dot{m} c_p (T_1 - T_2) \quad (3.4)$$

With the help of equation (3.4) determine the value of experimental heat transfer coefficient of heat pipe under free convection.

### 3.2.2 Analytical method to find heat transfer coefficient for natural convection

Firstly, we calculate the following parameter to find out the external heat transfer coefficient of condenser section of heat pipe.

#### a) To find film temperature, $T_f$ ( $^{\circ}\text{C}$ )

$$T_f = \frac{(\text{Average wall temperature of condenser} + \text{Ambient temperature})}{2} \quad [56]$$

With the help of film temperature, note down the thermo-physical properties of air at corresponding film temperature such as kinematic viscosity, thermal conductivity, Prandtl number and coefficient of volume expansion.

#### b) To find Grashof Number (Gr):

$$\text{Gr} = \frac{g\beta(T_c - T_a)L^3}{\nu^2} \quad [57]$$

Characteristic length of fins surface is calculated by following basic definition;-

$$L = L + t/2 \quad [11]$$

#### c) To find Rayleigh Number (Ra):

$$\text{Ra} = \text{Gr} * \text{Pr} \quad [23]$$

#### d) Flow condition:

(1) If value Ra is more than  $10^9$ , then flow is turbulent

(2) If value Ra is less than  $10^9$ , then flow is laminar. [58]

#### e) Nusselt Number, Nu:

Nusselt number can be obtained from Churchill and Chu empirical relation.

(i) If Ra lie between  $10^{-1} < \text{Ra} < 10^{12}$ , then Nusselt number for all entire range of Ra can be calculated by using following equation.

$$\text{Nu}_{\text{plate}} = \left\{ 0.825 + \frac{0.387 \text{Ra}_6^{1/4}}{\left[ 1 + \left( \frac{0.492}{\text{Pr}} \right)^{9/16} \right]^{4/27}} \right\}^2 \quad [59]$$

(ii) If Ra lie between  $0 < Ra < 10^9$ , then Nusselt number for laminar can be calculated by following equation.

$$Nu_{plate} = 0.68 + \frac{0.670 Ra_6^{\frac{1}{4}}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}} \quad [60]$$

If the heat pipe in the form of cylindrical shape. So the corrected Nusselt number for cylinder can be determine by using equation 3.11

$$Nu_{corrected} = Nu_{plate} (1 + 1.43 \xi^{0.9}) \quad [61]$$

Where,

$$\xi = \left(\frac{L}{d_o}\right) Gr^{-1/4}$$

**f) To find heat transfer coefficient:**

$$h = \frac{Nu k_{air}}{L} \quad [62]$$

The analytical heat transfer coefficient can be compared with experimental value and to find out the percentage deviation between experimental heat transfer coefficient and analytical heat transfer coefficient [63, 64].

### 3.3 Summary

The details about copper water heat pipe with annular fins and the experimental set up are given in this chapter. Which type of empirical co relation and experimental formulae are used related to heat pipe also discussed in this chapter. The instruments used in this setup are seen to be accurate from there calibration graphs. The parameter like condenser heat transfer coefficient with annular fin at different inclination under natural convection can be determine by experimental and analytical method. The result can be validated between results calculated from experiment and empirical formulas can be measured.

This chapter discussed the results obtained after the experimentation of heat pipe that is made of copper with annular fins over condenser section under free convection. Condenser heat transfer rate was calculated for each mass flow rate and for each angle of inclinations obtained experimental results and then compared to analytical model. While, carrying out the experimental range of mass flow rate and angle of inclination was kept at 40 to 200 ml/min and 0 to 45° respectively.

#### **4.1 Condenser heat transfer coefficient at different mass flow rates and tilt angles.**

The empirical correlations established by Churchill and Chu for flat plate has been used to predict the heat transfer coefficient on the condenser side of copper water heat pipe. Outside condenser heat transfer coefficient calculated by the analytical model and results obtained from experiments. The graphical comparisons among natural convection heat transfer coefficients for experimental results and that of different empirical correlations can be seen is shown in Figure 4.1. The percentage deviation between Churchill & Chu (laminar range) and experimental of 19.25%, 20.4%, 19.20%, 18.2% and 19.60% was seen. Similarly, the deviation between Churchill & Chu (all entire range of Ra) and experimental of 10.23%, 10.11%, 9.85%, 10.45% and 9.54% was seen in Figure 4.1. It has been observed that the heat transfer coefficient calculated by Churchill & Chu empirical correlations for laminar range is spurred as compared to experimental value. It also noticed that heat transfer coefficient predicted by Churchill & Chu empirical correlations for all entire range is close as compared to experimental value.

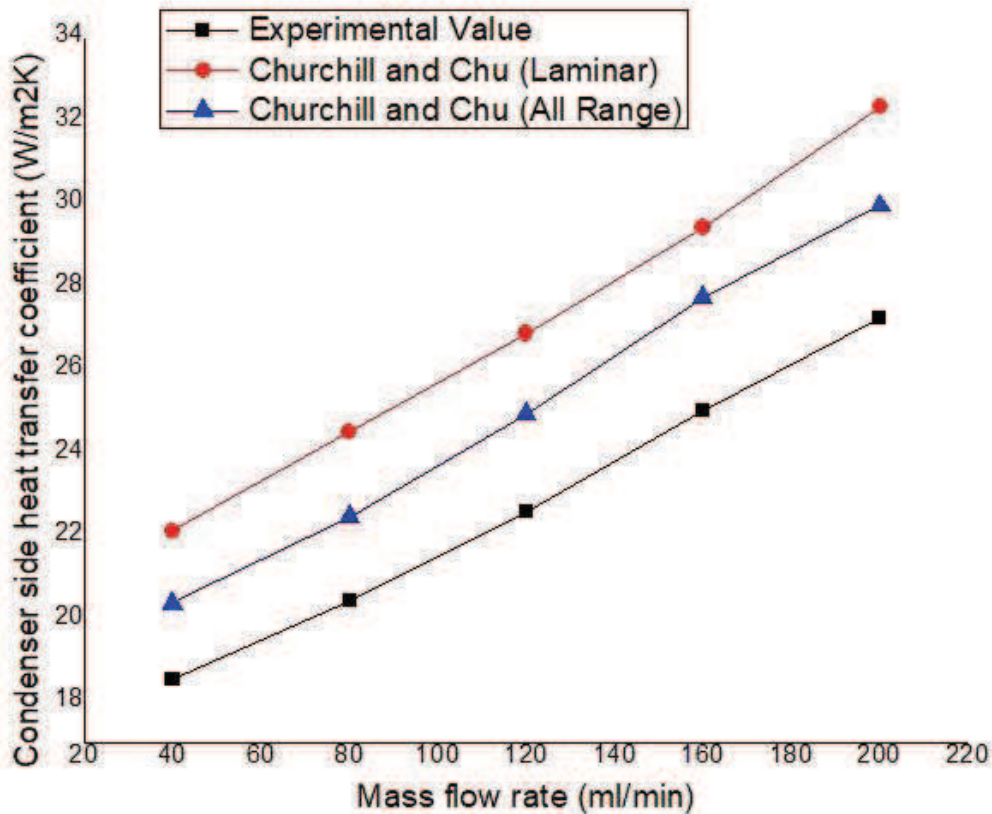


Figure 4.1 variation of condenser heat transfer coefficient with mass flow rate at 0° inclination

A graphical comparisons between experimental results and Churchill & Chu empirical correlations as shown in Figure 4.2. In this graph, the x-axis represent mass flow rate in ml/min and y-axis represents condenser heat transfer coefficient of heat pipe in W/m<sup>2</sup>-K. The following points was observed from the Figure 4.2.

- With the increase in mass flow rate, the rate of condenser heat transfer coefficient also increases because due to mass flow rate is linearly proportional to heat transport rate.
- It found that the condenser heat transfer coefficient calculated by Churchill & Chu (laminar) is high (6 to 22%) as compared to experimental value.
- It also found that condenser heat transfer coefficient calculated by Churchill & Chu for all entire range is close (2 to 11%) as compared to experimental value.

- The maximum heat transfer coefficient was found by experimental is  $29.23 \text{ W/m}^2\text{-K}$  at  $5^\circ$  inclination it is little more as compared to  $0^\circ$  inclination because it is possible better buoyancy driven flow in annular finned surface of condenser.

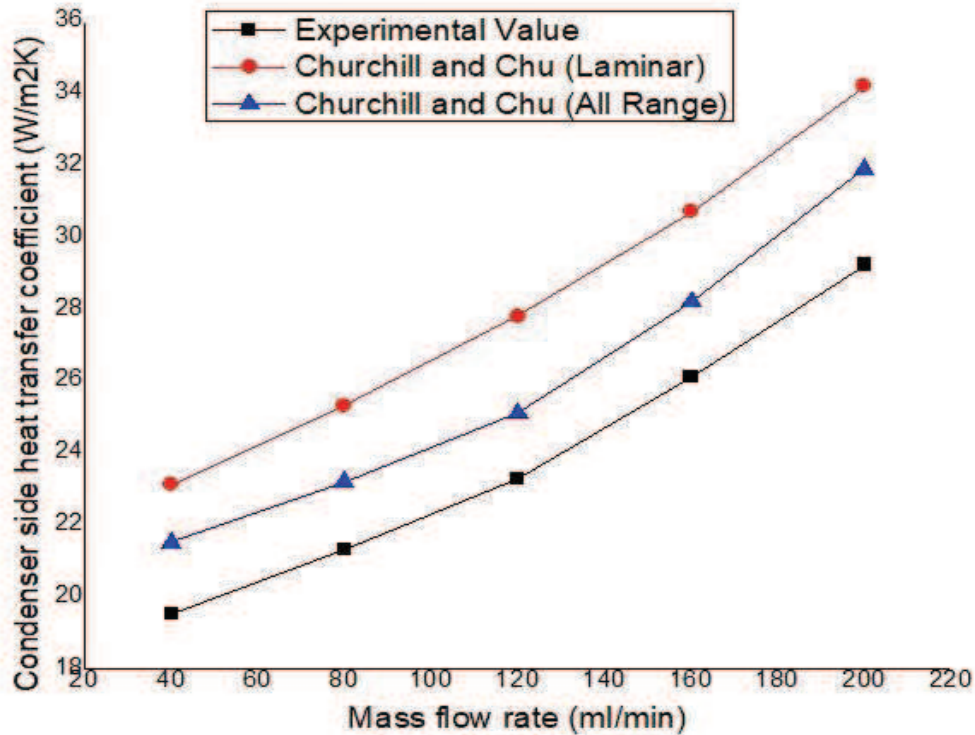


Figure 4.2 variation of condenser heat transfer coefficient with mass flow rate at  $5^\circ$  inclination

The Figure 4.3 represent the deviations between experimental value and Churchill & Chu empirical correlations at  $10^\circ$  inclination. At this inclinations followings points are noticed:-

- Inclination angle also effect the condenser heat transfer coefficient because it would possible with the increase of inclination angle heat transport rate increases and optimum rate of evaporation and condensate return to the evaporator, which result in lower thermal resistance. With the increase in inclination angle heat transfer coefficient also increase.

- At this inclination the percentage deviation between Churchill & Chu for laminar and results obtained from experimental is 19.36%, 20.2%, 21.2%, 20.1%, and 20.23%.
- At 10° inclination the percentage deviation between Churchill & Chu for all range and experimental is 11.10%, 10.8%, 9.78%, 8.7% and 9.45%.
- The maximum heat transfer coefficient was found by experimental 29.8 W/m<sup>2</sup>-K is more as compared to condenser heat transfer coefficient at 5° inclination i.e. with increase the angle of inclination heat transfer coefficient increase due to lower thermal resistance [39].

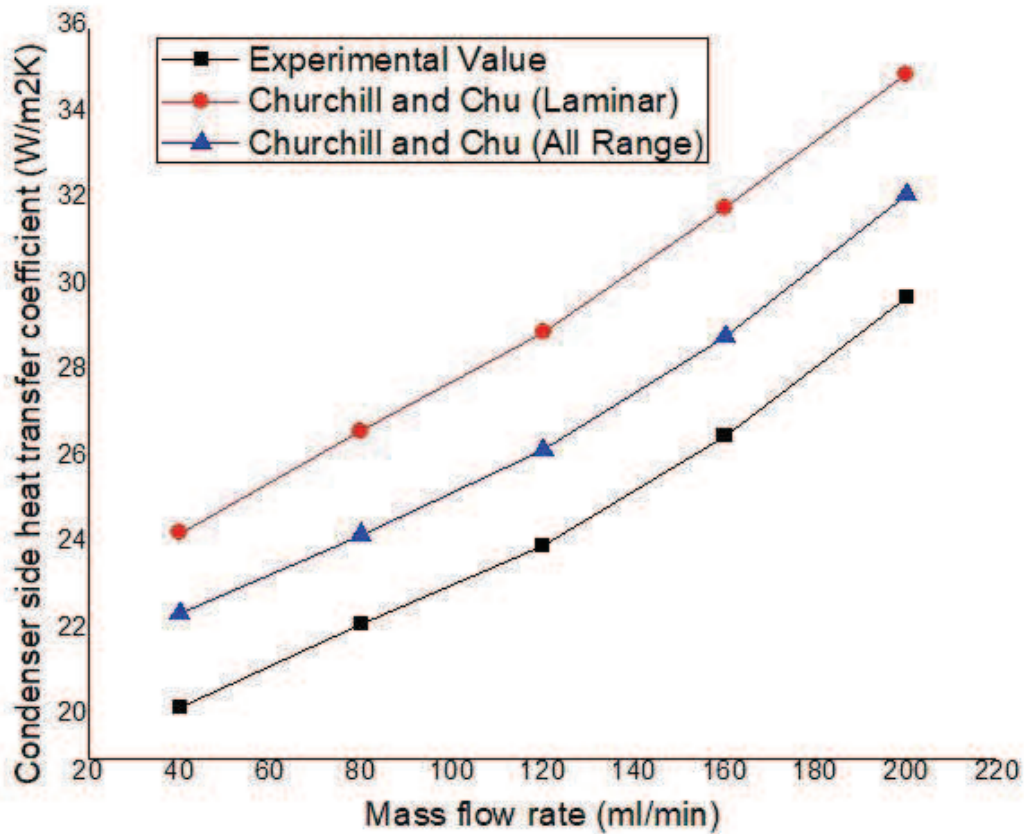


Figure 4.3 variation of condenser heat transfer coefficient with mass flow rate at 10° inclination

The graphical comparisons among free convection heat transfer coefficients for experimental results and that of empirical correlations can be seen in Figure 4.4. The x-axis represents the mass flow rate in ml/min and y-axis represents the condenser heat transfer coefficient in  $W/m^2-K$ . From this graph following points was observed:-

- Mass flow rate is linear proportional to the external condenser heat transfer coefficient.
- At this inclination the percentage deviation between Churchill & Chu for laminar and experimental within the range 6 to 21%.
- At this inclination the percentage deviation between Churchill & Chu for entire range and experimental within the range 2 to 11%.
- The maximum heat transfer was noticed at this inclination is  $30.2 W/m^2-K$  by experimental at 200 ml/min.

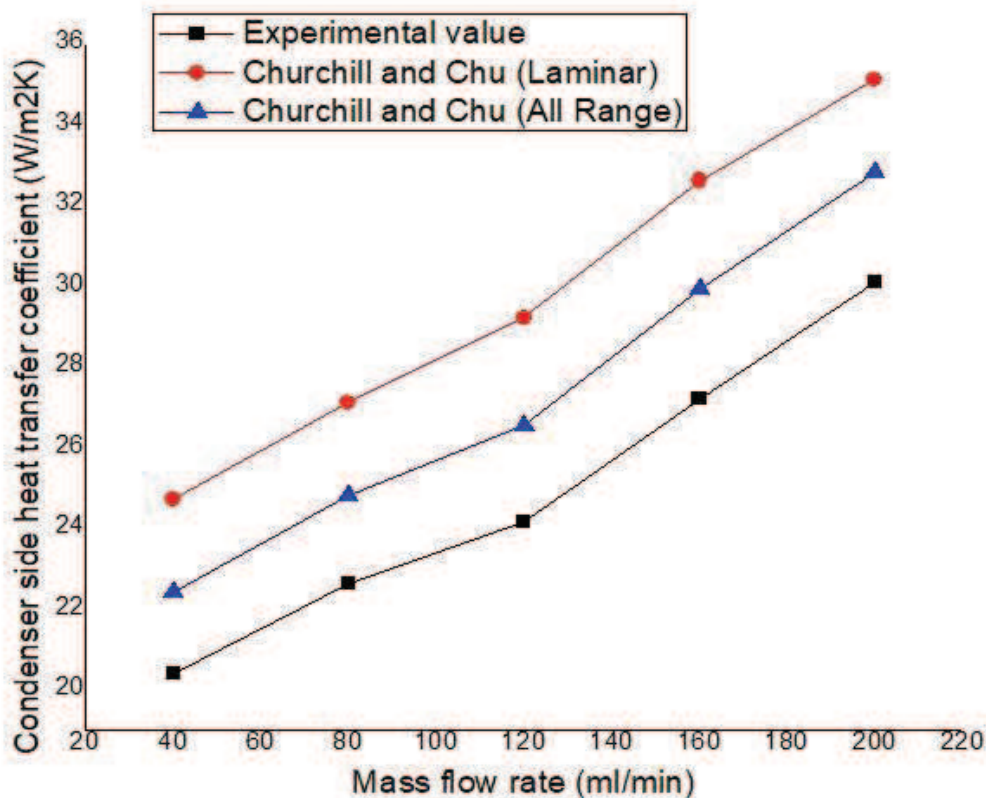


Figure 4.4 variation of condenser heat transfer coefficient with mass flow rate at 15° inclination

From Figure 4.5 represent the variation of condenser heat transfer coefficient with mass flow rate at 20° inclination. This figure presented the percentage deviation between results obtained from the experimental and result calculated by analytical model. At this angle of inclination following point is observed.

- In terms of percentage deviations of 20.25%, 18.91%, 19.26%, 19.67% and 20.67% corresponding to 5 different mass flow rate starting from 40 ml/min to 200 ml/min were observed between experimental results and empirical prediction from Churchill and Chu for laminar. As seen from Figure 4.5, the variations between empirical results from Churchill and Chu for all range and experiments were significantly less compared to previous case with changes of 10.34%, 9.89%, 10.34%, 8.45% and 10.19%. All these deviation were within permissible limit [64].

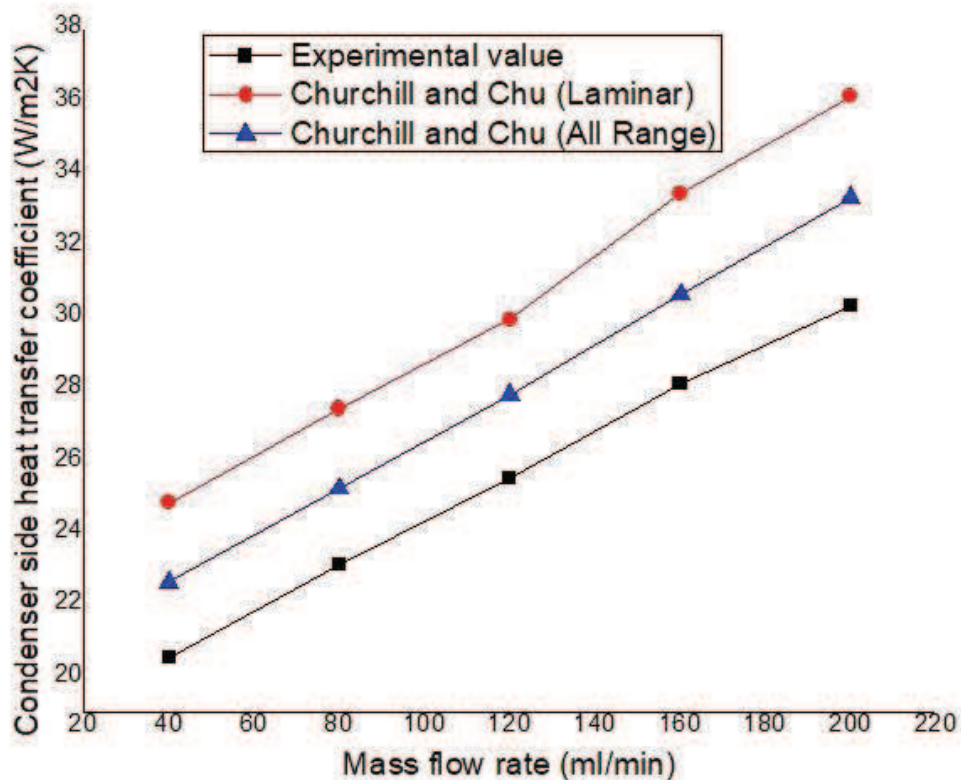


Figure 4.5 variation of condenser heat transfer coefficient with mass flow rate at 20° inclination

A graphical comparisons between experimental results and Churchill & Chu empirical correlations as shown in Figure 4.6. In this graph, the x-axis represent mass flow rate in ml/min a y-axis represents condenser heat transfer coefficient of heat pipe in  $W/m^2-K$ . The following points was observed from the Figure 4.6.

- At this inclination the maximum condenser heat transfer coefficient was found  $31.2 W/m^2-K$  at 200 ml/min mass flow rate due to better exposure of condenser annular finned surface to ambient environment and the optimum rate of evaporation and condensate return to the evaporator, which results in its lower internal and external thermal resistance.
- The condenser heat transfer coefficient, predicted by Churchill and Chu for all range of Rayleigh number is closer (2 to 11%) to the experimental value as compared to Churchill and Chu correlation for laminar range, which varied in the range of (5 to 22%)

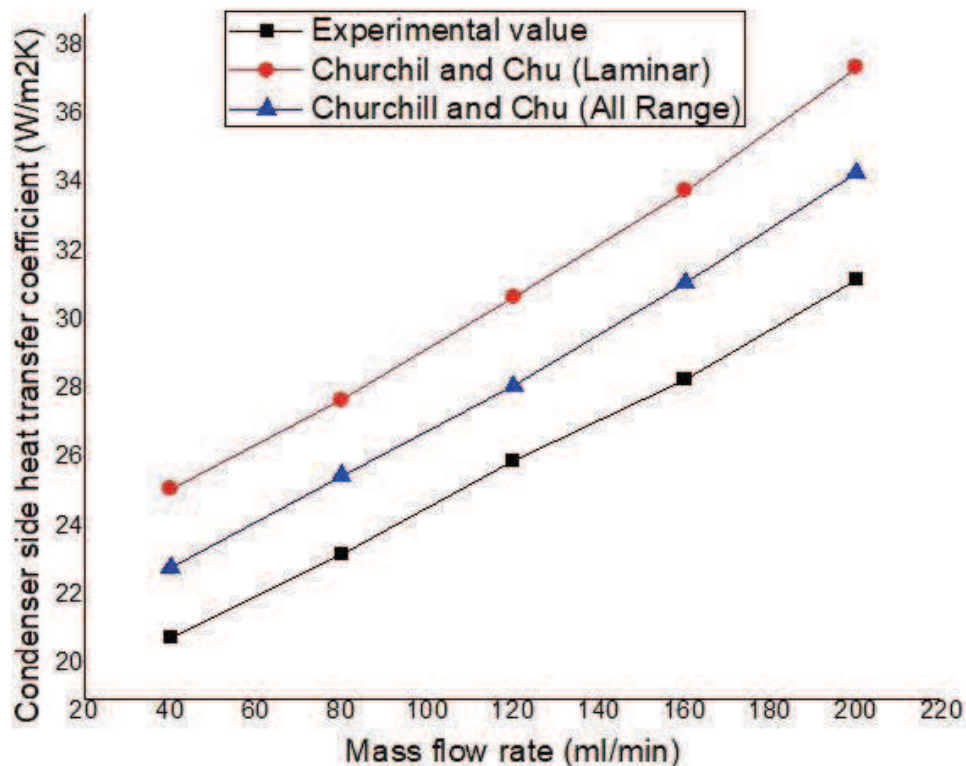


Figure 4.6 variation of condenser heat transfer coefficient with mass flow rate at 25° inclination

From Figure 4.7 presented the percentage deviation between results obtained from the experimental and result calculated by analytical model. At this angle of inclination following point was observed.

- At this inclination it was found that condenser heat transfer coefficient was started decreased as compared to condenser heat transfer coefficient at 25° inclination because temperature of condenser part start increases, as the boundary layer may not be fully developed at the bottom surface of annular fins.

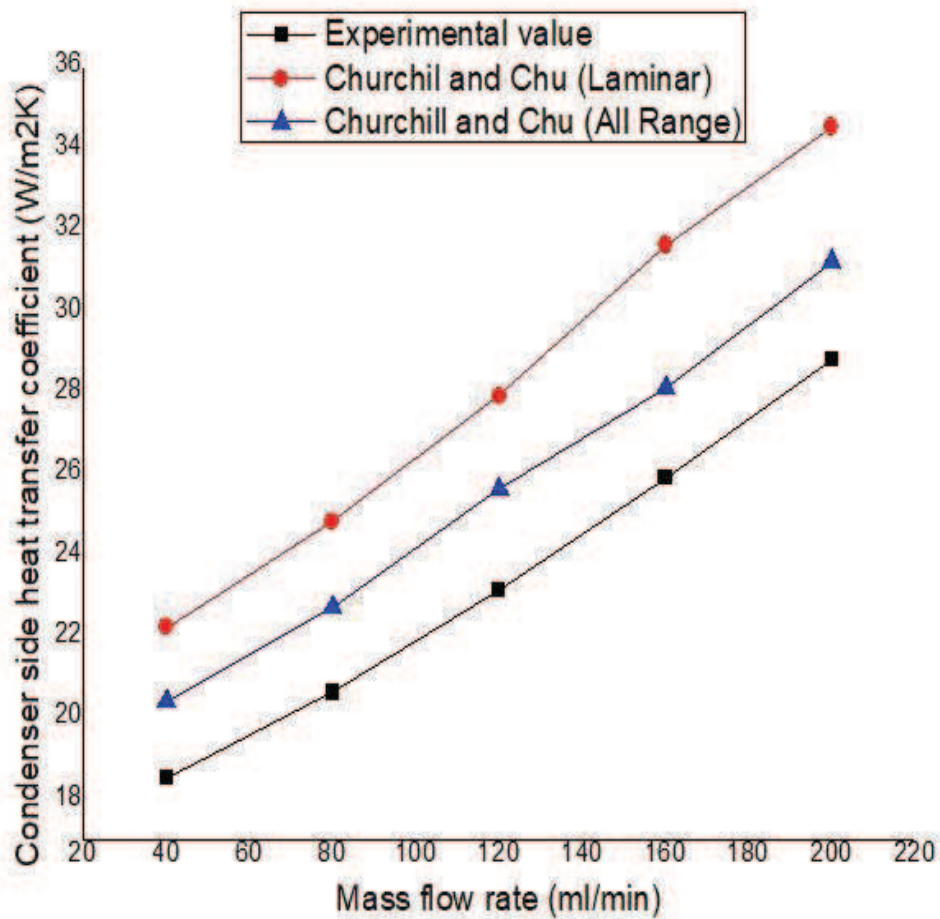


Figure 4.7 variation of condenser heat transfer coefficient with mass flow rate at 30° inclination

From Figure 4.8 represent the variation of condenser heat transfer coefficient with mass flow rate at 35° inclination. This figure presented the percentage deviation between results obtained from the experimental and result calculated by analytical model. At this angle of inclination following observation was found:-

- It found that beyond the 25° inclination condenser heat transfer coefficient start decreases. It also noticed that at this angle maximum condenser heat transfer coefficient is 12.5% less as compared to 25° inclination angle due to less amount of heat transferred at this angle. The best thermal performance of heat pipe has been reported in the range of 15-30° inclination by various authors [59-61].

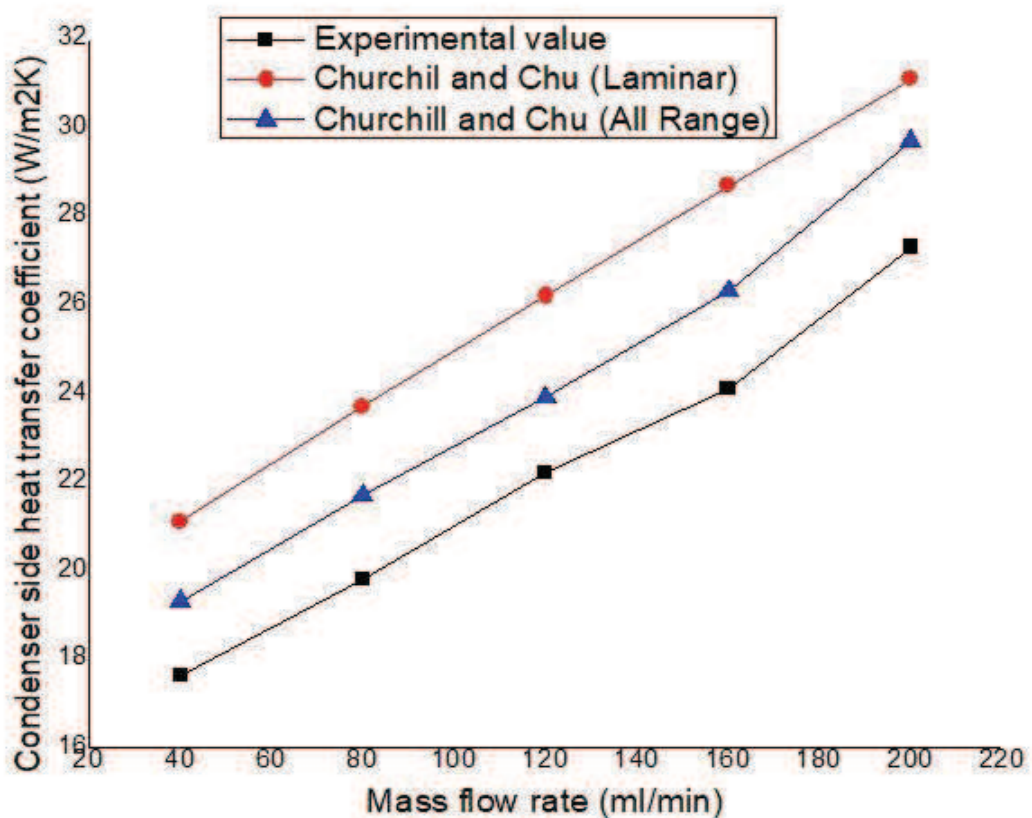


Figure 4.8 variation of condenser heat transfer coefficient with mass flow rate at 35° inclination

From Figure 4.9 represent the variation of condenser heat transfer coefficient with mass flow rate at 40° inclination. This figure presented the percentage deviation between results obtained from the experimental and result calculated by analytical model. At this angle of inclination following point was observed.

- In terms of percentage deviations of 21.25%, 19.91%, 20.26%, 18.67% and 21.67% corresponding to 5 different mass flow rate starting from 40 ml/min to 200 ml/min were observed between experimental results and empirical prediction from Churchill and Chu for laminar. As seen from Figure 4.9, the variations between empirical results from Churchill and Chu for all range and experiments were significantly less compared to previous case with changes of 9.34%, 10.89%, 8.34%, 9.45% and 10.19%. All these deviation were within permissible limit [64].
- It also found that maximum condenser heat transfer coefficient is less as compared to 25° inclination angle.

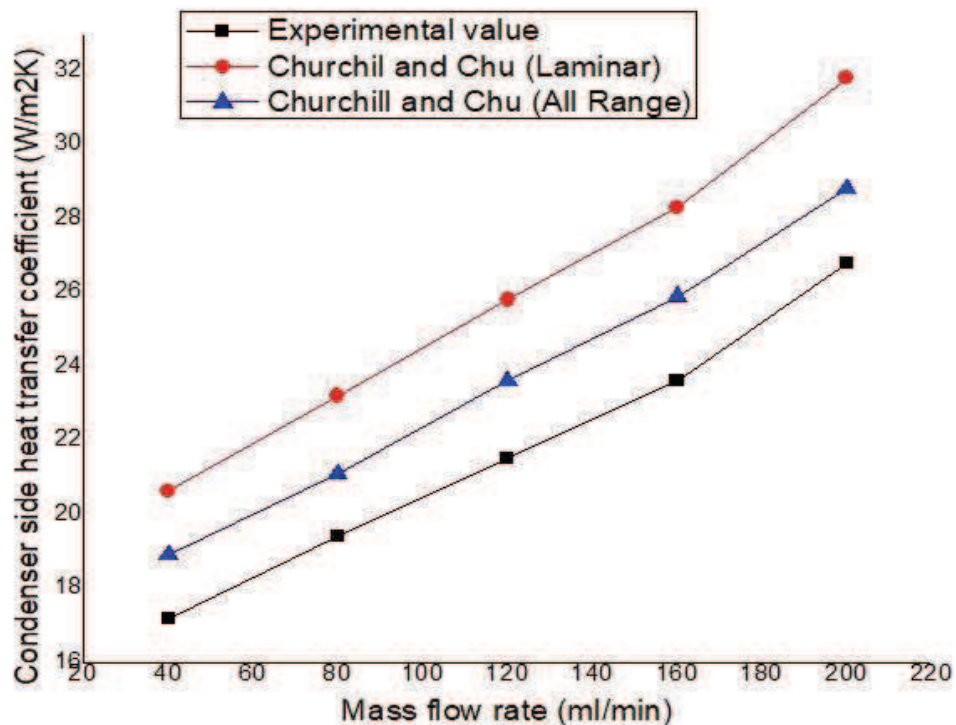


Figure 4.9 variation of condenser heat transfer coefficient with mass flow rate at 40° inclination

The graphical comparisons among free convection heat transfer coefficients for experimental results and that of empirical correlations can be seen in Figure 4.10. The x-axis represents the mass flow rate in ml/min and y-axis represents the condenser heat transfer coefficient in  $W/m^2-K$ . From this graph following points was observed:-

- At this inclination the percentage deviation between Churchill & Chu for laminar and experimental within the range 6 to 21%.
- At this inclination the percentage deviation between Churchill & Chu for entire range and experimental within the range 2 to 11%.
- All these deviation within permissible limit [39].
- The maximum condenser heat transfer coefficient was found  $26.41 W/m^2-K$  is 18.2 % less as compared to  $25^\circ$  inclination angle due to condenser dry-out.

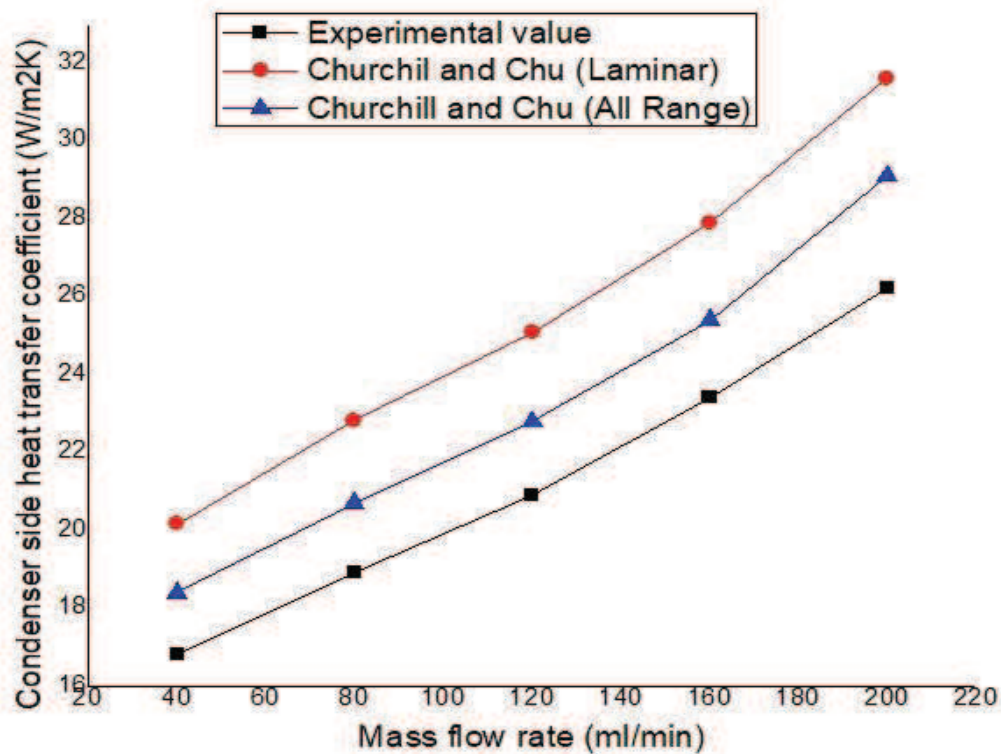


Figure 4.10 variation of condenser heat transfer coefficient with mass flow rate at  $45^\circ$  inclination. The condenser heat transfer coefficient, which showed a linear increase with mass flow rate. Corresponding to 10 different tilt angles of heat pipe ( $0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ, 25^\circ, 30^\circ, 35^\circ, 40^\circ$ , and  $45^\circ$ )

five different mass flow rate were applied over the evaporator section (40ml/min, 80ml/min, 120ml/min, 160ml/min and 200 ml/min). So a set 50 experiments were performed to determine at what inclination angle and at what mass flow rate give maximum condenser heat transfer coefficient. The maximum condenser heat transfer coefficient of 31.2 W/m<sup>2</sup>-K was observed at 200 ml/min for 25° tilt angle. On average, the minimal condenser heat transfer coefficient of 26.4 W/m<sup>2</sup>-K was seen at vertical 45° heat pipe tilt. Graphical results for the same are demonstrated in Figure 4.11. Similar results were reported by some researchers too which proved that 15° to 30° is the best inclination range for heat pipe [59-61]. The graphical comparison of heat pipe condenser heat transfer coefficient to different tilt angles and mass flow rate can be seen in Figure 4.11.

Table 4.1: Condenser heat transfer coefficient (W/m<sup>2</sup>-K) of copper water heat pipe at different mass flow rate and tilt angles

Parameters varied	40 ml/min	80 ml/min	120 ml/min	160 ml/min	200 ml/min
0° tilt	18.50	20.40	22.26	24.98	27.21
5° tilt	19.50	21.30	23.28	26.10	29.23
10° tilt	20.20	22.10	23.92	26.50	29.70
15° tilt	20.40	22.60	24.12	27.20	30.10
20° tilt	20.50	23.10	25.50	28.10	30.30
25° tilt	20.80	23.20	25.90	28.30	31.20
30° tilt	18.46	20.60	23.10	26.30	29.10
35° tilt	17.60	19.80	22.20	24.10	27.30
40° tilt	17.20	19.40	21.50	23.60	26.80
45° tilt	16.80	18.90	20.90	23.40	26.40

From the Figure 4.11, it is clear that condenser heat transfer coefficient was maximum at 25° inclinations as compared to other inclination angle. At this angle heat transfer is maximum because it would be possible better buoyancy driven flow in condenser section. The best thermal performance of the heat pipe under this operating condition may be attributed due to better exposure of condenser annular finned surface to ambient environment and the optimum rate of evaporation and condensate return to the evaporator, which results in its lower internal and external

thermal resistance. After 25° inclination heat transfer rate goes on decreasing. This is primarily due to the fact that beyond 25° inclination may be restriction of boundary layer formation at higher angle of elevation that lead to reduction of heat transfer coefficient at higher orientation. Experimental results obtained showed the similar behavior as obtained by Kumar et al [39]. . It is reported that variation in the experimental heat transfer and Churchill and Chu (for laminar range) was around 22%. For all range of Rayleigh was observed to be in the range of 11%. Literature reports that the calculated heat transfer coefficient may vary  $\pm 25\%$  from the actual value in natural convection [51].

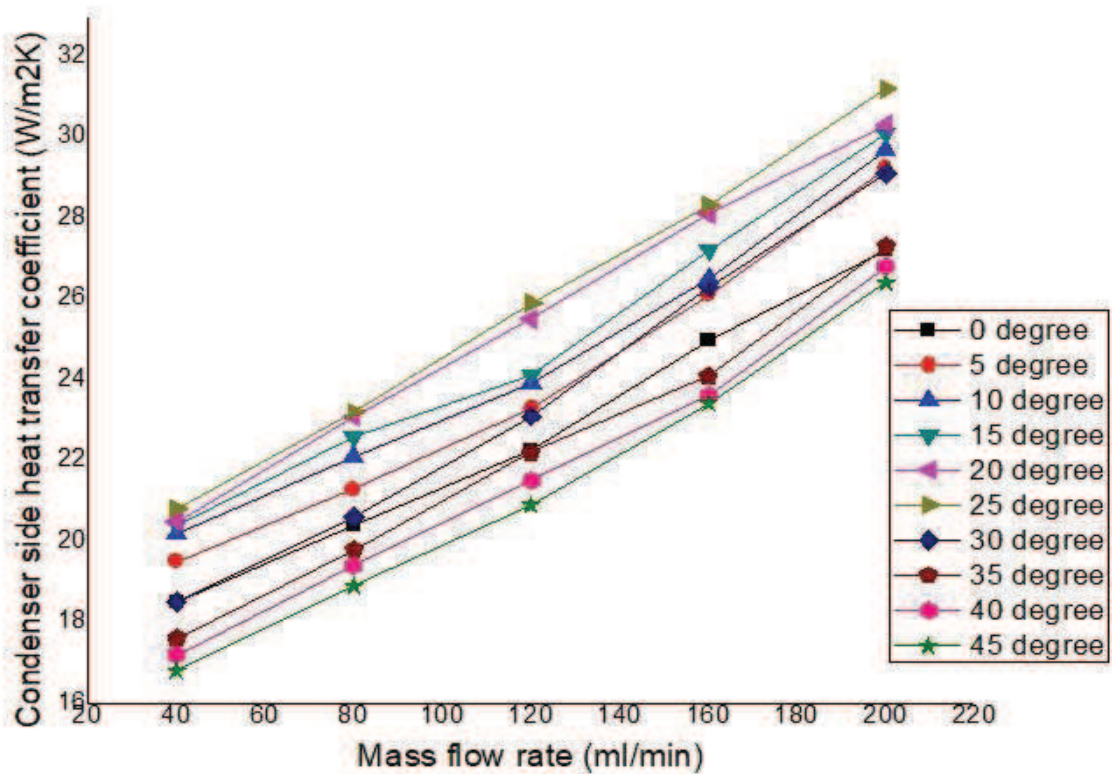


Figure 4.11 comparisons of condenser heat transfer coefficient with mass flow rate at different angle of inclination.

Heat pipe of different types, specifications, dimensions and materials will produce different condenser heat transfer coefficient. There is no particular inclination angle that can be considered

valid and reliable for all heat pipes. Working fluid as well as container materials also play a vital role in deciding the thermal performance of heat pipe as discussed in Chapter 2. The results shown in this section are for a 180 mm long with 7.8 mm diameter copper heat pipe. It is not advisable to operate water heat pipe beyond 30° inclination angle because it showed deteriorated performance due to less heat exposure to ambient.

#### 5.1 Conclusions

This chapter depicts, the conclusion drawn from the experimental result are discussed. There was numerous experiment were conducted on a straight copper water heat pipe with annular fins under natural convection to examine it performance at different inclination. The analytical model has been developed to predict the individual heat transfer coefficient at the surface of condenser. The noticeable observation can be drawn from present investigation are as follow.

- With the increase in mass flow rate, the rate of heat transfers of heat pipe also increases due to mass flow rate is linearly proportional to the heat transfer coefficient.
- The heat transfer coefficient over condenser section with annular fins, under free convection increases with the increase in heat input on the evaporator section.
- The predicted heat transfer coefficient by Churchill and Chu (for laminar flow) and experimental heat transfer coefficient were in fair agreement with deviation no more than 22%.
- The predicted heat transfer coefficient by Churchill and Chu (for all range of Rayleigh number) and experimental heat transfer coefficient were in fair agreement with deviation no more than 11%
- It was envisaged, that inclination angle had the most significant effect on heat pipe performance. It concluded that heat transfer rate of heat pipe increase when heat pipe operates between inclinations at  $0^\circ$  to  $25^\circ$  because due to better exposure of condenser annular finned surface to ambient environment. Beyond,  $25^\circ$  heat transfer rate start decrease.
- Noticeable, enhancement was found in heat transfer coefficient with annular fins over condenser section under natural convection. The maximum heat transfer coefficient under free convection was  $31.2 \text{ W/m}^2\text{-K}$  at  $25^\circ$  inclination and least was obtained at  $45^\circ$  inclinations because rate of heat transport is less at this angle, which may be due to poor buoyancy driven flow in annular finned surface of condenser.

- The condenser temperature is high at 45° tilt angle, but at this angle condenser heat transfer is low because may be of incomplete formation of boundary layer.

## **5.2 Future scope**

In this scenario, heat pipe technology is adopted by a lot of industries. A lot of research work has been done in this field. The following are the suggest work for future scope:

- From the previous literature I was found that coating of fin has great effect on the performance of heat pipe so before fin placed over the condenser section coating is must to enhance the rate of heat transfer. The thermal contact resistance between fin and heat pipe surface could be reduced by using coating or soldering technique without damage the heat pipe surface.
- To improve the thermal performance of fins with the increase in the relative humidity of the ambient air.
- New material of fin should be selected in such a way that it would serve two purpose one is cost effective and second is high ability to heat transfer coefficient.
- The dimension of various components like evaporator, adiabatic and condenser can be further altered in order to enhance heat transport rate.

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Table A1: Calibration data of rotameter (all readings in ml/min)

<b>Flow rate</b>	<b>Test 1</b>	<b>Test 2</b>	<b>Test 3</b>	<b>Test 4</b>	<b>Test5</b>
30	30	31	30	31	30
60	61	60	62	61	60
90	91	90	91	92	90
120	120	121	121	120	121
150	149	150	150	149	150

Table A2: Calibration data of temperature sensors on water heat pipe (all readings in °C)

<b>Thermometer Readings</b>	<b>TS-1</b>	<b>TS-2</b>	<b>TS-3</b>	<b>TS-4</b>	<b>TS-5</b>	<b>TS-6</b>
20	20	20	21	22	19	20
30	29	30	32	31	30	31
40	40	39	40	42	40	40
50	50	51	51	52	51	50
60	61	60	60	61	60	59
70	70	70	71	71	70	72

Table A3: Temperature of heat pipe data at 0° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	61	59	54	54	55	53
80	63	62	56	56	57	55
120	64	63	57	56	58	56
160	64	63	59	58	60	58
200	65	64	59	59	61	59

Table A4: Temperature of heat pipe data at 5° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	62	60	53	53	54	52
80	63	62	55	54	57	55
120	64	63	58	58	60	58
160	64	63	59	59	61	60
200	65	64	60	59	60	59

Table A5: Temperature of heat pipe data at 10° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	61	59	52	51	52	50
80	62	61	56	56	58	56
120	63	61	57	57	59	57
160	64	63	59	59	60	58
200	65	64	60	59	61	60

Table A6: Temperature of heat pipe data at 15° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	61	59	52	51	52	50
80	62	61	56	55	57	55
120	63	62	58	57	59	57
160	63	62	60	59	61	59
200	65	64	61	60	62	60

Table A7: Temperature of heat pipe data at 20° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	60	58	52	51	52	50
80	62	61	57	56	58	56
120	63	62	60	59	61	59
160	64	63	60	60	61	59
200	65	64	60	60	62	60

Table A8: Temperature of heat pipe data at 25° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	62	60	53	52	53	51
80	63	62	58	57	59	57
120	64	63	59	58	60	58
160	65	64	59	59	60	59
200	65	64	60	59	61	59

Table A9: Temperature of heat pipe data at 30° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	60	58	52	51	52	51
80	62	61	56	55	58	56
120	63	62	59	58	61	58
160	64	63	61	60	62	60
200	65	64	62	61	63	61

Table A10: Temperature of heat pipe data at 35° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	61	59	54	53	54	53
80	63	62	58	57	59	57
120	64	63	59	59	61	59
160	65	64	59	58	60	59
200	65	64	61	60	62	60

Table A11: Temperature of heat pipe data at 40° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	61	59	54	54	56	54
80	62	61	58	57	59	57
120	63	62	60	59	61	59
160	64	63	60	60	62	60
200	65	64	61	60	62	61

Table A12: Temperature of heat pipe data at 45° inclination

<b>Mass flow rate ml/min</b>	<b>TS-1 °C</b>	<b>TS-2 °C</b>	<b>TS-3 °C</b>	<b>TS-4 °C</b>	<b>TS-5 °C</b>	<b>TS-6 °C</b>
40	62	61	55	55	57	54
80	64	63	58	57	60	58
120	65	64	59	59	61	60
160	65	64	59	60	62	61
200	65	64	61	60	63	62

### **PUBLICATION BASED ON THE RESEARCH WORK**

- Singh S, Sharma S, Gangacharyulu D, “ A Review of Extended Surface in Heat Transfer Problems”, International Journal of Engineering Research & Technology (IJERT), Vol.7 Issue 07, July-2018
- Singh S, Sharma S, Gangacharyulu D, “ Experimental Investigation of Heat pipe with Annular Fins Under Natural Convection At Different Inclinations ”, International Journal of Engineering Research & Technology (IJERT), Vol.7 Issue 07, July-2018

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