Northern Arizona University

# "*Heat Pipe Demonstration Unit*"

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# Final Report

**Project Sponsor:**

**Dr. David Trevas**

# DISCLAIMER

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# EXECUTIVE SUMMARY

Heat pipes are utilized for transporting heat between points. The working liquid touching the part of the pipe with high temperature will vaporize while keeping the pipe at that same temperature. Typically, this is used in electronic devices, such as computing devices. It forms a part of the cooling structure in many devices, especially the high-power elements, including the computer's central processing unit, to eliminate the excess heat produced from the device. This paper analyzes various significant factors in the design of heat pipes. It will focus mainly on the pressure and on the thermal conductance. The subsystems that will be considered in this project are heating pipe material, wick material, and cooling fluid. This project aims to provide preliminary analysis on future studies on heat pipes by maximizing the efficiency through choosing an optimal combination of the said subsystems.

For the heat pipe material, the initial options are copper, aluminum, and iron. For the wick material, the options are grooved wick, metal mesh, and metal-sintered powder mesh. For the cooling liquid, the options are water, aluminum, and methanol. The available options will be discussed further in this paper, as well as how the team came up with the optimal solution. This paper also explains how quartz glass can also be a good heat pipe material.

After conducting experiments, the optimum combination of material that the team has concluded for maximum efficiency is using quartz glass heat pipe using water as a cooling fluid. A heater tape was also used as a safer alternative for candle as a heat source.

When designing heat pipes, it is important to choose materials that are economical and readily available. In addition, it is critical for the selected material to be easily modifiable as per the desired specifications, especially in the internal structure of the pipe. The material should be of low weight so as to make the finished product light. This consideration is especially needed for portable electronic devices, such as laptops. Heat pipe designers should select materials based on their physical properties. Besides, the material should fit into the targeted working conditions. Hence, resistance to environmental factors, including thermal and chemical attacks, is a necessary trait. Lastly, the material for the design of heat pipes should have a high enough melting point to prevent operational failures arising from thermal effects.

# ACKNOWLEDGEMENTS

Heat pipe team has been helped by our client Dr. David Trevas and our teaching assistance Amy Swartz.

Dr. Trevas guided us in the engineering principles. Amy Swartz assisted us in the technical writing by giving us comments.

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# 1 BACKGROUND

## 1.1 Introduction

Demonstration units are used in laboratory classes in the Mechanical Engineering Department at Northern Arizona University (NAU) to teach students engineering principals. Our project is to build a heat pipe demonstration unit, which will help students understand the basic principles of heat transfer and thermodynamics. A heat pipe is pipe filled with a liquid and a wicking material that transfers heat much faster than a stand-alone pipe because it uses conduction and convection as opposed to conduction alone [1].

A heat pipe is a heat-transfer gadget that joins the standards of both warm conductivity and stage change to viably transfer heat between two strong interfaces. The working liquid touching the part of the pipe with high temperature will vaporize while keeping the pipe at that same temperature. The vapor at that point goes along the heat pipe to the chilly interface and gathers once more into a fluid – discharging the inactive heat [2]. The fluid at that point comes back to the hot interface through either fine activity, diffusive power, or gravity, and the cycle rehashes. Because of the simple high heat transfer coefficients for bubbling and buildup, heat pipes are very viable warm conductors. The successful warm conductivity changes with heat pipe length. Heat pipes are commonly used in electronics and space applications, where rapid heat transfer to remove heat from the system is necessary [3].

The sponsor for this project is our instructor, Dr. David Trevas. This project will be beneficial to the stakeholders such as mechanical engineering students and faculties at NAU because this can serve as a preliminary analysis and a guide for further studies in heat pipes.

## 1.2 Project Description

Our team has been tasked with designing and building a heat pipe demonstration unit for a mechanical engineering laboratory class at NAU. First, we will research on the different alternatives of working fluids, wicking materials, and heat pipe material which are available [4]. Then, we will be testing these alternatives in consideration with pressure and thermal conductance. We will determine the optimum combination of these parameters that will result to high heat pipe efficiency. We will design a heat pipe using the chosen materials and test it through laboratory experiments.

The main objective of this capstone design project titled "***Heat Pipe Demonstration Unit***" is to study the main characteristics and specifications of heat pipe, such as the thermal response-time for heat pipe and compare it to a regular copper rod, Measure and report the response-time and temperature profile along the heat pipe, and finally calculate the effective thermal conductivity for the heat pipe and compare it to with high thermal conductivity alternatives. And finally compare different scenarios for the wick materials.

# 2 REQUIREMENTS

In this section, it contains the requirements that team need to design a heat pipe in mechanical engineering laboratory, including the customer needs, engineering requirements, and house of quality (HoQ). The customer and engineering requirements for this capstone project arise from the demand of electronics industry stakeholder and space applications. These requirements need to be met during the different stages of the project. House of Quality (HoQ) is a tool which will determine which factors are deemed important by the customers. It takes into consideration the 7 management and planning tools including the affinity diagram, relation diagrams, tree diagram, matrix diagram, arrow diagram, PDPC and Matrix data analysis. With the help of this there is a smooth transition between the customer's request to creating engineering requirements.

## *2.1 Customer Requirements (CRs)*

Customer requirements (CRs) were generated by meeting with our client and discussing what is most important for this project. Additional CRs were taken by looking at existing designs for heat pipes and what their advantages are disadvantages. The CRs for this project are given in in Table 1.

Table 1. Customer Requirements.

| Customer Requirement | Description | Weight |
| --- | --- | --- |
| Durability | How long it is withstanding | 0.16 |
| Accuracy | How accurate it will work | 0.16 |
| Manufacturalble | Rate which it could be mass produced | 0.11 |
| Safety | How safe the heat pipe setup is for the end user | 0.13 |
| Ease of Assembly | Time to install the parts | 0.14 |
| Variability | Capable of varying with the situation | 0.17 |
| Easy to Measure | Measuring of the temperature is easy | 0.13 |

The above customer requirements are the main factors customer will require when purchase the heat pipe. The team weighted CRs based on their importance. The highest weights of 0.17 were given to variability. This is given the higher weight because they are fundamental to everyday usage. Following these high weights comes durability and accuracy at 0.16. This is because the heat pipe must be durable with stand the thermal load for long time and can be rely on when we use to sink the heat from the heat source. The next weight comes in at 0.14 for ease of assembly. This was assigned the weight of 0.14 because they are important for the product to be installed easily and be user friendly. The next lowest weight comes from safety at 0.13. This is because safety of the human being is very important especially in mechanical engineering laboratory. The lowest weighted requirement is to be manufacturable and operate in various conditions, with a weight of 0.11. This is because while cost is important, the team will design the heat pipe in excellent way to satisfy this factor.

## 2.2 Engineering Requirements (ERs)

Engineering requirements (ERs) were generated from CRs. Table 2 is a summary list of engineering requirements created by meeting with our client to fit the CRs and meet the engineering design principles. The team set up targets for each ERs. These are targets that should be accomplished, if the team need to override them that will be completed. For instance, the setup time is 1 min. When the team finished the design, and had some changes, the targets will be moved forward to achieve optimum performance.

Table 2. Engineering Requirements.

| ERs | Description | Targets |
|---|---|---|
| Material Melting Temperatures | The materials must be able to withstand the maximum operating temperatures of 200℃. | 200℃ |
| Reliability | Being able to switch fluids, pressure and wicking materials. | 5 years |
| Set-up time | Able to set up the experiment within 1 min. | 1 min |
| size | Volume, size of the set up to be useable for lap demo. | 12 cubic feet |
| Light Weight | Light weight to utilize it in better way | 5 Kg |

## 2.3 House of Quality (HoQ)

House of quality is a matrix which tells the factors that are important to the customers. Therefore, it is vital to relate engineering requirements with the CR's and see which engineering requirement is most important from the list and which must be focused on. HoQ do the same thing and it gives the Relative Technical Importance and Absolute Technical Importance. From the RTI, we got the priority order list of engineering requirement. Highest percentage of RTI is most important and lowest percentage of RTI is least important engineering requirement.

In the above Table 3, the team relate the customer requirements to the engineering requirements. A high number in the intersection of the row for CR and column in ER dictates the strength of relationship between the two. For example, durability has a relationship of 9 with material melting point while it has only 1 with set-up time. This means that the material melting temperature will greatly affect the durability while set-up time will not affect it. This was done in all CRs and ERs. A strength number of 8-10 means that it has strong relationship, 5-7 is moderate relationship, and 1-4 is weak relationship. Also seen in the HOQ is the importance number, the higher the number, the more important the customers feel about that certain aspect. For example, durability has an importance number of 9. This means that the customers greatly desire a durable product. This is basically a reflection of the CRs. The number in each column is multiplied by its corresponding importance number then it is summed. The number with the highest column sum means that the ER in that column must be prioritized by the team in designing the heat pipe.

In Table 3, it was also found out that size is the most important factor to consider and it will affect the design of project maximum and on number second in importance list is material melting temperature setting, third is reliability, fourth in the list of important factors is Setup time and the least important factor is light weight. So, the weight isn't affecting much to the project, but size of the product will affect maximum to the project.

Table 3. HoQ.

| Customer Requirements \ Engineering Requirements | Importance | Material Metling Temperatures | Reliability | Setup Time | Size | Light Weight |
|---|---|---|---|---|---|---|
| Durability | 9 | 9 | 3 | 1 | 1 | 1 |
| Reliability | 3 | 3 | 9 | 3 | 9 | 3 |
| Manufacturable | 3 | | | | 3 | |
| Safety | 9 | 3 | 3 | 3 | 9 | 1 |
| Easy to Assembly | 9 | 1 | 1 | 3 | | 3 |
| Variability | 1 | | 1 | 3 | 1 | 1 |
| Easy to Measure | 3 | 1 | 9 | 9 | 3 | 3 |
| **Technical Importance: Raw Score** | | 129 | 118 | 102 | 136 | 64 |
| **Technical Importance: Relative Weight** | | **23.5%** | **21.5%** | **18.6%** | **24.8%** | **11.7%** |
| **Techanical Target Value** | | 200 | 5 | 1 | 12 | 5 |
| **Upper Target Limit** | | | | | | |
| **Lower Target Limit** | | | | | | |
| **Units** | | C | Years | Min | ft^3 | Kg |

# 3 EXISTING DESIGNS

This part includes the research that the team has conducted into what subsystems already exist for the heat pipe. Researching these systems was mainly done by searching for previously done thoroughly for the heat pipe.

## 3.1 Design Research

The main objective of this capstone design project titled "***Heat Pipe Demonstration Unit***" is to study the main characteristics and specifications of heat pipe, such as the thermal response-time for heat pipe and compare it to a regular copper rod [5]. Then, measure and report the response-time and temperature profile along the heat pipe and calculate the effective thermal conductivity for the heat pipe compared with high thermal conductivity alternatives. Finally compare different scenarios for the wick materials.

In this project, firstly a qualitative analysis will be made to assess the thermal response time of a copper-water heat pipe, at the moment it is put in a hot and cold water in row and compare that to the copper rod with same size and the same length [3]. After the qualitative observation, a horizontally heat pipe made of a copper as manufacturing material, a copper wick, and water will be the working fluid will be tested and thermal characteristics will be concluded, during this part variation of parameters will be there to see how the thermal characteristics will be changed.

To simulate the hot side a flexible heater will be wrapped on one side of the heat pipe and will be secured using clips. The other side is the uncovered portion of the heat pipe will be exposed to the surroundings (ambient temperature) and works as the condenser section that is cooled down by natural convection. Then a k-type thermocouples will be installed at the condenser side. Those thermocouples will be connected to a data acquisition system to record and monitor the temperature readings recorded by thermocouples. The input power given to the electric heater will play an important role when studying the effect of the hot side in the whole heat transfer process, simply the input power to the heater can be calculated by multiplying the input rated current by the input rated voltage of the heater [6].

## 3.2 System Level

A heat pipe is a passive heat transfer equipment which has the ability to transfer heat with very small temperature gradient if compared to high thermal conductivity metals such as copper [7]. Three sections can characterized in a heat pipe, the evaporator, the condenser, and the adiabatic section [8]. Evaporator part sinks the heat from the high temperature side and convert the coolant or the working fluid to vapor inside. First, it will vaporize then by latent heat, the fluid will condensate. At low temperature, the latent heat will allow the vapor to condensate. The condensate will go back to the evaporator using the wick.

However, in case that the pipe has no wick, it will utilize gravity to return [9].

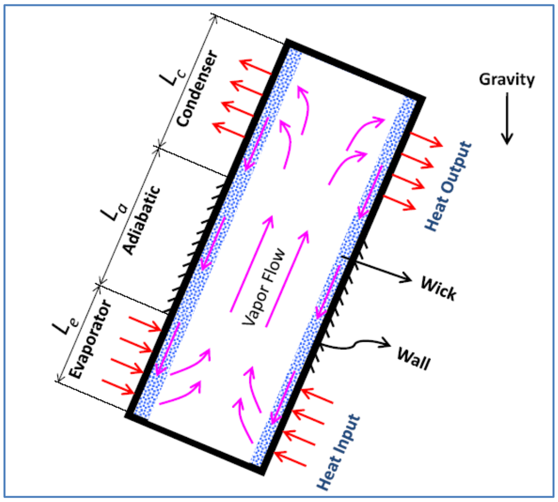



Figure 1.  Schematic view of Heat Pipe

A heat pipe is mainly composed of a vacuum envelope, a wick structure and a working fluid (Figure 2). The heat pipe is totally evacuated and then filled again with a little quantity of working fluid (coolant), an amount just to fill the wick. Because the coolant is the vital member in the heat pipe, the pressure inside the pipe is the same as the saturation pressure accompanied with the heat pipe temperature. When the heat enters at the evaporator, equilibrium is disturbed, this will cause vapor to generate at a little higher pressure and temperature. The higher pressure leads vapor to travel to the condenser end where the slightly lower temperature leads the vapor to condensate and release its latent heat of vaporization. This condensate will now return to the evaporator by virtue of capillary forces through the wick. This going on cycle can transfer large amounts of heat even with very small thermal gradients. A heat pipe's operation is passive, being leaded only by the heat that it transfers, which consequently will result in high reliability and long life [10].

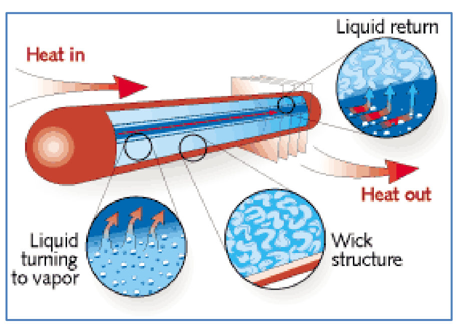



Figure 2. The Structure and functioning of a heat pipe.

Heat pipes can transport a wide range of power. This will depend mainly on the design on which the pipe was created as well as the application that it aims to provide. For a given thermal gradient, heat pipes is able to transfer comparably more heat than even the metal conductors. When loaded beyond its nominal capacity, however, the effective thermal conductivity of the heat pipe will be dramatically decrease. Therefore, it is very important to design the heat pipe to safely transport the required heat. Heat transfer capability of the heat pipe is depending on several limiting factors viscosity, capillary pumping, flooding and boiling.

### 3.2.1 Existing Design #1: Grooved base type

This design, as shown in Figure 3 has a heat exchanger that allows flat pipes to be connected. This is very helpful in this design since it is basically a combination of the local heat sink and the remote heat sink. The remote heat sink was incorporated to maximize the thermal performance [7]. This design is lighter and cheaper compared to other designs.

Figure 3. Grooved base type Heat Pipe.

### 3.2.2 Existing Design #2: Grooved mounted block type

The second existing design is shown in Figure 4. The heat pipes are mounted in holes. These holes are typically bigger by 0.1 mm [7]. If the pipes are more round at the heat source, a thicker grooved mounting plate is needed as seen in Figure 4.

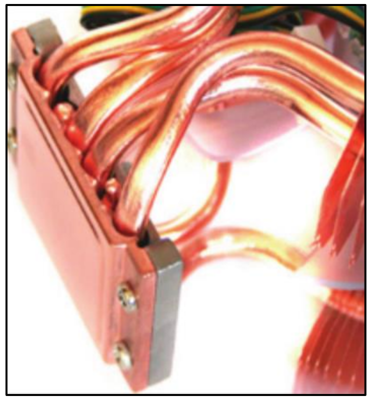


*Figure 4*. Grooved Mounted Block Type Heat Pipe.

### 3.2.3 Existing Design #3: Direct contact type

The third existing design is shown in Figure 5. Sometimes, much heat is lost because of the base plate and extra TIM layer, thus, additional flatting and machining is needed to enable more fluid to touch the surface as seen in Figure 5 [7]. This is a good heat sink since it can decrease the temperature by as much as 2 to 8 degrees Celsius

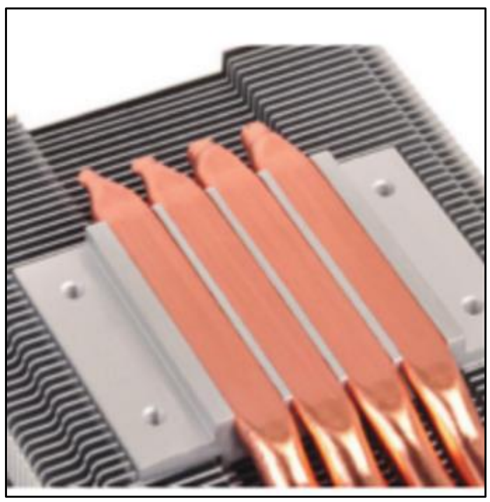


Figure 5. Direct Contact Type Heat Pipe.

## 3.3 *Functional Decomposition*

Functional decomposition is a process of decomposing the complete working module for the project. This is the expected working of product, observed after seeing the existing designs. There are two types of functional decomposition, one is black box model and second is functional model. Black Box model shows the inputs and outputs of the system in the form of material, energy and signal. Functional model shows the internal working of the project and show the processes that uses by the product to convert the input into the output.

### 3.3.1 Black Box Model

The Black Box model shows the inputs and outputs of system. It doesn't matter what is the internal working of system. It only focuses on the inputs going into the system and outputs that are coming out form the system. The Black Box model shows the inputs as "Material (Hand, Wick materials, and Liquid), Energy (Electric Energy), Signal (On/Off, Temperature dial, and pressure)" and the outputs as "Material (Hand), Energy (Heat and cool), Signal (On/Off, Temperature Reading pipe)". Black Box model has shown in Figure 6.

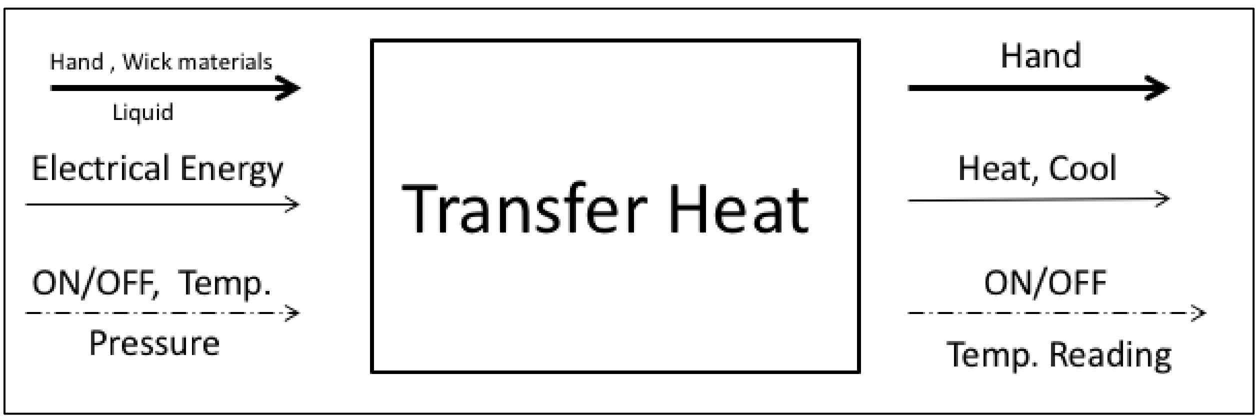



Figure 6. Black Box Model.

### 3.3.2 Hierarchical Task Analysis

Functional model shows the inside of Black Box. It shows the inputs of system and all the processes that perform inside the system to produce the outputs. Functional model takes each step that performs inside the body of any product in the form of box and get the output. For our project system, it will take the heat into the pipe, that heat the liquid present in the pipe. It will convert the liquid into vaporize liquid and then vapors will move towards the condenser to get cool, at the same time some of the vapors raise the temperature of wicking material and cool down the vapors by absorbing the heat. The vapors go to the condenser also gets cooled and release the cooling and the cycle restart again by absorbing the heat and cool down the system.

Shown in Figure 7 is a model showing the heat import first from the source into the pipe, and then covert that heat so that the source will get the cooling and heat will remain into the sink.

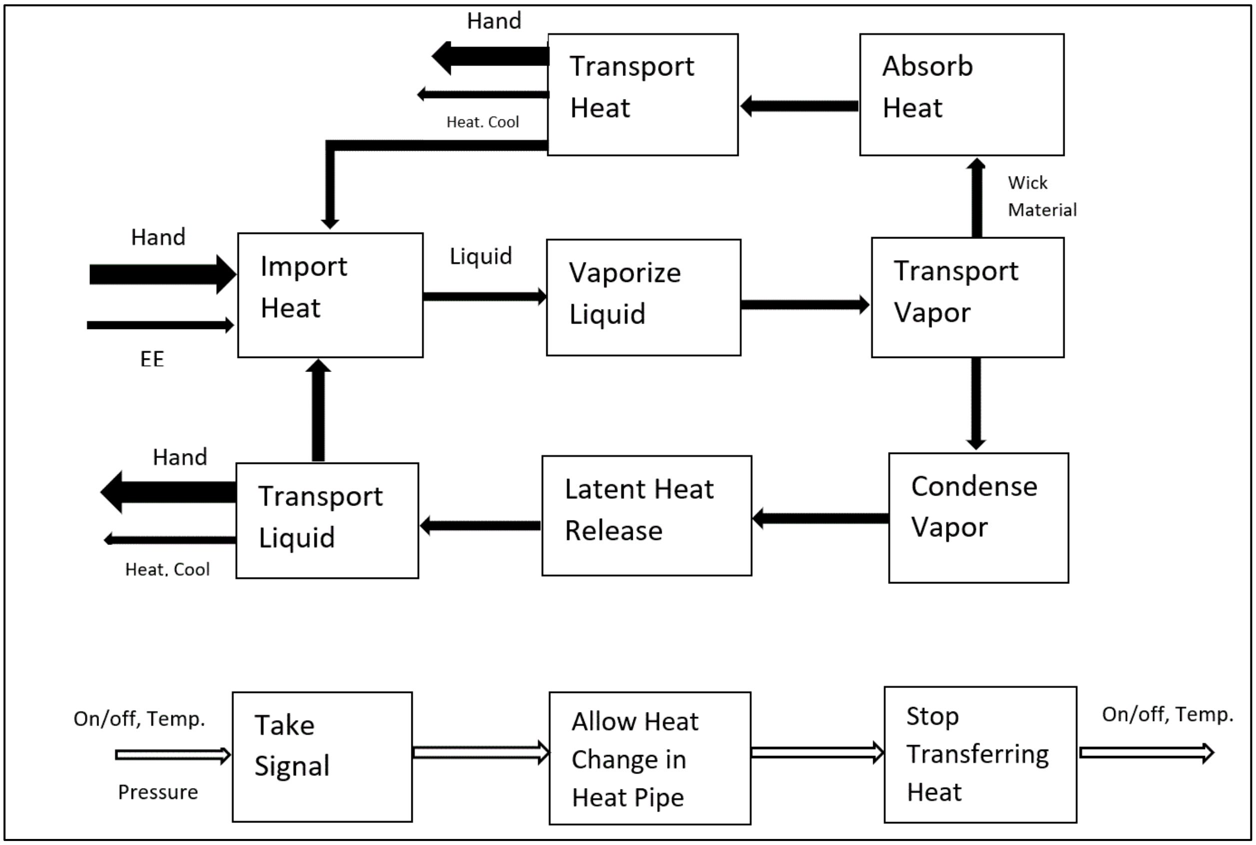



Figure 7. Functional Decomposition Model.

## 3.4 Subsystem Level

The Heat pipe setup construction can be broken down into the main subsystems which is the heat pipe material, wick material, and working fluid. It has a few options for design that the team had to consider when picking a design.

### 3.4.1 Subsystem #1: Heat pipe material

Heat pipe material is important because it will dictate the working temperature and pressure of the pipe. It will provide a vessel so that the working liquid will not leak.

#### 3.4.1.1 Existing Design #1: Copper

Copper pipes are durable, lightweight and easy to work with which makes it a typical choice. It is corrosion-resistant. It is also less expensive while being environmentally friendly.

Figure 8. Copper pipe

#### *3.4.1.2 Existing Design #2: Aluminum*

Aluminum pipe are usually used for high-temperature piping. It is usually used in spacecraft thermal control.

Figure 9. Aluminum pipe

#### *3.4.1.3 Existing Design #3: Iron*

Iron pipe has high machinability and good wear-resistance. It is more preferred for high pressure loads.

Figure 10. Iron pipe

### 3.4.2 Subsystem #2: Wick Material

In this section, the different types of wick materials that can be used in heat pipes are further discussed. Consideration of the wick material to be used is very important because it can improve the condenser's heat transfer rate, which is directly proportional to the heat pipe's efficiency.

#### *3.4.2.1 Existing Design #1: Grooved wick type*

In this design, see Figure 11, a grooved heat pipe is a copper tube with a series of shallow grooves on the inside face of the pipe. The performance of heat pipes with axial groove wicks is very good, provided that the application does not call for a significant adverse elevation against gravity. For systems that employ up to 40 $W/cm^2$ of radial heat flux, this design is usually used.

Capillary action is affected by the grooves on the inside of the heat pipe. The efficiency of this design depends on the shape of the grooves. Manufacturing costs are low with this type of heat pipe because the grooves are easier to make, however the technique is much more susceptible to gravity and can be orientation specific in use.

Figure 11. Grooved Wick Type Heat Pipe

#### *3.4.2.2 Existing Design #2: Metal mesh (felt) wick type*

As shown in Figure 12, the wick of this type is a metal mesh. The mesh is adhered to the inside wall of the pipe. This will allow heat transfer by capillary forces in the wick. This is one of most commonly used type of wick. Its heat transfer capability is greatly affected by the number of layers and mesh counts used in the wick.

Sometimes a metal felt based wick structure is used which is held in support by a metal foam. Usually, copper and stainless steel are used to manufacture the metal mesh. By varying the pressure on the felt during assembly, various pore sizes can be produced. By incorporating removable metal mandrels, an arterial structure can also be molded in the felt. These methods serve in increase the capillary strength of the wick which translates into even better heat pipe performance.

Heat pipes with screen mesh wick structures are capable of operating in gravity-aided and horizontal orientations and are capable of returning the working fluid against gravity at angles up to 5˚ from horizontal. These heat pipes can also be used in applications with radial heat fluxes up to 40 W/cm2.

The few times we have dissected a heat pipe here this is the kind of metal wick structure we discovered. In a freshly cracked open heat pipe the wick would be slightly wet.

Figure 12. Metal Mesh (felt) Wick Type.

#### *3.4.2.3 Existing Design #3: Metal sintered powder wick type*

In metal sintered powder, see Figure 13, the sintered powder sticking to the inside walls of the pipe. This transfer the cooling fluid by a process called capillary action. It is important to be knowledgeable on this design well because this is a powerful design especially when dealing with designs that are not in the direction of gravity. This design allows very tight bends in the heat pipe.

.

Figure 13. Metal Sintered Powder Wick.

### 3.4.3 Subsystem #3: Working fluid

Working fluid is important because it will transfer heat by through evaporation and condensation. It gives the heat pipes high effective thermal conductivity. A liquid's pumping capability is measured by Merit number. The higher the Merit number, the better.

#### *3.4.3.1 Existing Design #1: Water*

Water is the most common, cheapest and safest cooling fluid in existent. It has the highest Merit number among all other cooling fluids at around 1.77894E+12.

#### *3.4.3.2 Existing Design #2: Ammonia*

Ammonia is usually used in high temperature heat pipes like a spacecraft thermal control. It is also used together with an aluminum pipe. It has around 3.19972E+11 Merit number at 20 degrees Celsius.

#### *3.4.3.3 Existing Design #3: Methanol*

It usually used as an alternative when water and ammonia are not available or suitable with the heat pipe material. It has around 3.17293E+11 Merit number at 20 degrees Celsius and is the third highest among other fluids.

# 4 DESIGNS CONSIDERED

There are numbers of available fin designs available, each with their own cost and performance characteristics. It is vital to choose the best fit heat sink in designing a heat pipe because it will greatly affect the heat transfer rate. In choosing heat exchanger, specifically, one must consider the forced convection involved in the system. So below is a list of the considered design with typical benefits and potential pitfalls.

## *4.1 Design #1: Extruded heat sink*

One of the most effective way of sinking heat is through extruded heat sink (see Figure 14). In extruded heat sink an aluminum foil uses which cause the heat sink to operate in easy way and it sinks the heat quickly comparing with the other heat sinks. Following is the sketch of heat sink.

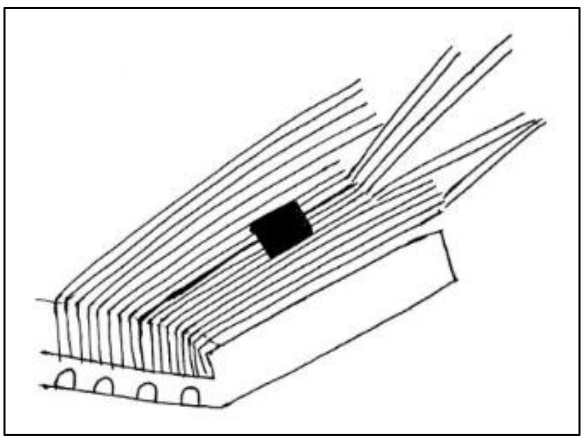


Figure 14. Extruded Heat Sink.

**Typical Benefits:**

Readily Available

Easy to manufacture to custom specifications

Including groove for heat pipe

**Potential Pitfalls:**

Dimensions are limited.

Fin height limited ~20x fin width

Base and fins are same material, usually aluminum

## 4.2 Design #2: Die cast heat sink

It is a type of heat sink which provide cooling to the system in which casting process happens, like the molten form of any material need the cooling so at that place heat sink play its role and cover heat evolve from the system. It can be seen in Figure 15.

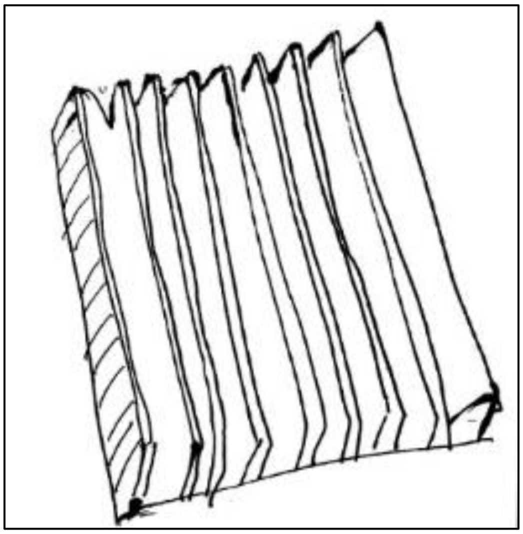


Figure 15. Die Cast Heat Sink.

**Typical Benefits:**

Net Shape

Low Weight

Easily customizable

**Potential Pitfalls:**

Lower thermal conductivity

Potential for porosity.

Not generally used with heat pipes.

## 4.3 Design #3: Bonded heat sink

In this design concept, bonded heat sink is present, this type of heat sink forms by the combination of plates with a great bonding present in them. The plates join together closely to form a linking system which sinks the heat as showing in Figure 16.

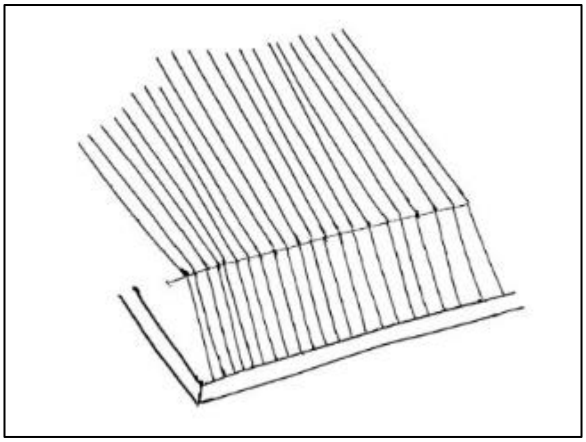


Figure 16. Bonded Heat Sink.

**Typical Benefits:**

Large heat sink sizes

Base and fins can be of different materials.

**Potential Pitfalls:**

If fins are epoxied in place, added thermal resistance.

## *4.4 Design #4: Skived*

It is a single form of block with cooper plating uses in it. It provides high cooling system because it is made up of skiving, with the stamped or folded fins. It can see in Figure 17.

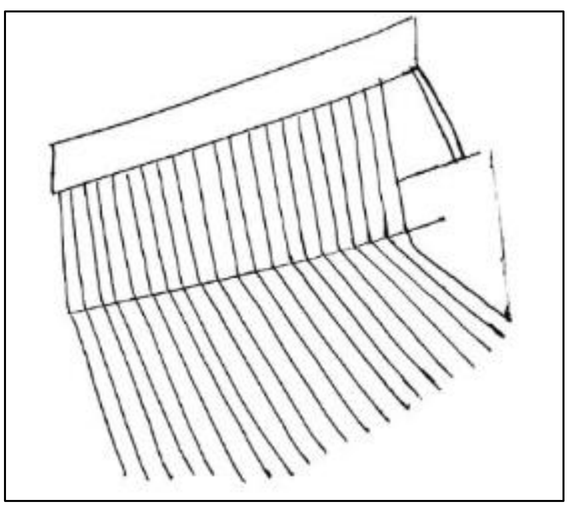


Figure 17. Skived Heat Sink.

**Typical Benefits:**

Fin and base from solid piece of metal, usually copper

High density fins possible.

More design flexibility than extrusion

**Potential Pitfalls:**

Base maybe thicker than needed, thus higher weight.

Fins damage easily.

## 4.5 Design #5: Fin pack and zipper fins

In this type of heat, all the fins are packed from both the sides and the fins have formed in the same way as a zip is present. There is a bend in the finds to make a look like zip. Zipper fins provide high cooling system because of its unique packing which have the capability to sink heat quickly and provide cooling quickly and it can be seen in Figure 18.

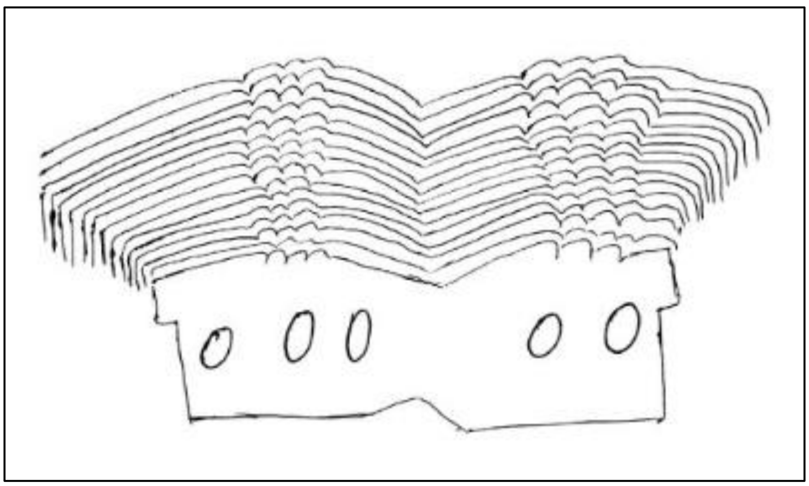


Figure 18. Zipper Heat Sink.

**Typical Benefits:**

Low-high fin density.

Low weight.

High design options, including center mounted heat pipes.

**Potential Pitfalls:**

Generally, for fins less than 1 mm. thick.

-Refer to the Appendix for the other available heat sink designs.

# 5 DESIGN SELECTED – First Semester

In this section, the team will discuss the main design selected for this project, and a clear justification why as a team will adopt this design, justifying the use of each component through the setup project. This optimized selection process will mainly be based on Pugh chart and decision matrix and also the data extracted from house of quality which is built on (HoQ) analysis. Also, the concepts mentioned in the previous section are individual design concepts and the team evaluated them. After eliminating, the team selected the best 3 concepts from the Pugh Chart. After that, the team used the decision matrix to select our final design.

## *5.1 Rationale for Design Selection*

In choosing the best design, the team utilized the Pugh Chart. This chart is used to compare the designs with the other design criteria. The left column includes the various design criteria's which the top horizontal row are the designs considered. The criteria's taken into consideration are durability, accuracy, manufacturability, safety, ease of assembly, variability and the ease of measuring. These criteria were also the ones considered in the House of Quality and as customer requirements. The composite wick heat sink here is considered as the datum design. The designs which are better that the datum are marked as "+" while those which are worse are marked as "- ". Those which are the same with the datum are marked as "S". The various rating for the criteria's based on the designs was make in each box and then summed at the bottom to obtain the ranking.

Each design was rated and the rates for each design are summed up. After that, the design with the most positive and least negative marks is chosen. In this particular group of design, the skived stood out with 4 positive marks, 2 neutral and 1 negative mark. Thus, the skived is considered the optimum design for this project (see appendix B).

The decision matrix in Table 4 was created to compare the designs based on various criteria's and to conclude as to the best design for this project. The various criteria considered were the material melting temperature, the reliability, set up time, size and weight. Skived had a better rating in terms of the material melting temperature where the temperature was the highest when compared to the other designs but on a reliability scale the bonded heat sink stood a better rating compared to the Skived. Bonded heat sink also stood a better rating at the setup time followed by Skived and then design die cast heat sink. In the size and light weight criteria Skived had the best rating compared to die cast heat sink and bonded heat sink. When all these criteria were taken into consideration and calculated it was observed that Skived had the best total rating of 88 making it the optimum choice for the project.

Table 4. Decision Matrix,

| Weight / Criterion | | Die cast | | | Bonded | | | Skived | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Material Melting Temperature | .235 | 80 | | 18.8 | 85 | | 19.9 | 95 | | 22.3 |
| Reliability | .214 | 70 | | 14.9 | 90 | | 19.3 | 80 | | 17.1 |
| Set-up Time | .186 | 85 | | 15.8 | 88 | | 16.4 | 78 | | 14.5 |
| Size | .248 | 79 | | 19.6 | 84 | | 20.8 | 95 | | 23.6 |
| Light Weight | .117 | 80 | | 9.4 | 85 | | 9.9 | 90 | | 10.5 |
| **Totals** | 1 | | | 78.5 | | | 86.3 | | | 88 |
| **Relative Rank** | | | | 3 | | | 2 | | | 1 |

In choosing the wick structure, it is vital to consider the role that the heat pipe will be used. There is no absolute best wick structure; it will always depend on its use. If a heat pipework in conditions with favorable gravitational force and a few bends, the grooved wick heat pipe is a good choice because of its superior thermal performance. If a heat pipe has a complex geometry and works at a small or negative tilting angle, sintered powder metal is the optimum wick structure. For cooling electronic components in telecommunications devices and computer products, the sintered powder metal wick is the best choice because such applications require a compact heat sink size with many turns and bends. The high capillary pumping pressure achieved by using a sintered powder metal wick due to its small pore size, allows a heat pipe to operate in any orientation. Other wick structures do not work as well as well in non-vertical orientations because they cannot lift the returning working fluid along the length of the heat pipe against gravity. So, in our heat pipe we primarily decided to choose the combination of sintered powder metal wick – inclined setup – skived heat sink, the main that motivate us to choose this design is the electronics applications which required such combination (see Figure 19).

Integrating Heat-pipe with a heat sinks built with cooling fin assemblies will provide one of the most effective means of providing efficient cooling for power electronics components. The forced air-cooled assembly shown opposite achieves an outstanding thermal performance.

With electronic components being the potential sites for heat generation due to their continuous miniaturization, it was identified that their life decreases by half for every 10-degree Celsius rise in temperature. This large amount of heat can be removed by use of different cooling methods available such as use of fans, blowers, heat exchangers or heat sinks.

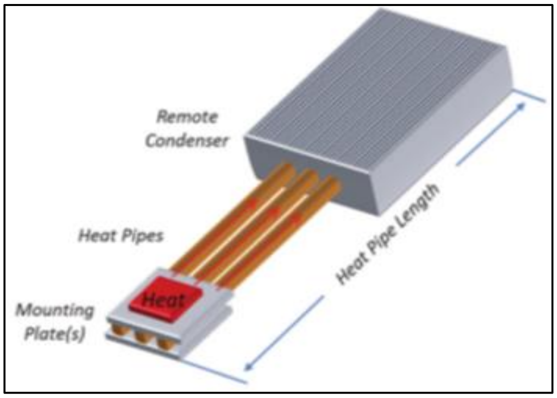


Figure 19. Heat Pipe Design Selected.

## 5.2 Design Description

There are five components that the team has considered as discussed earlier. These are the working fluid, heat flux, wick materials, pressure and thermal conductance. This section will focus on the chosen alternative for each of the components.

### 5.2.1 Prototype Design

For the prototype as shown in Figure 20, the heat pipe material that was used is copper. This comes with copper caps and a valve on the right side (see Figure 20). The length of the pipe is 2ft with an extension of 0.25 in. A candle was used as a heat source while a vacuum was used to control the pressure inside the pipe. A thermometer with thermocouple wires was also used to measure the temperature. The considerations used in choosing these features and specifications will be further discussed in the next sections.

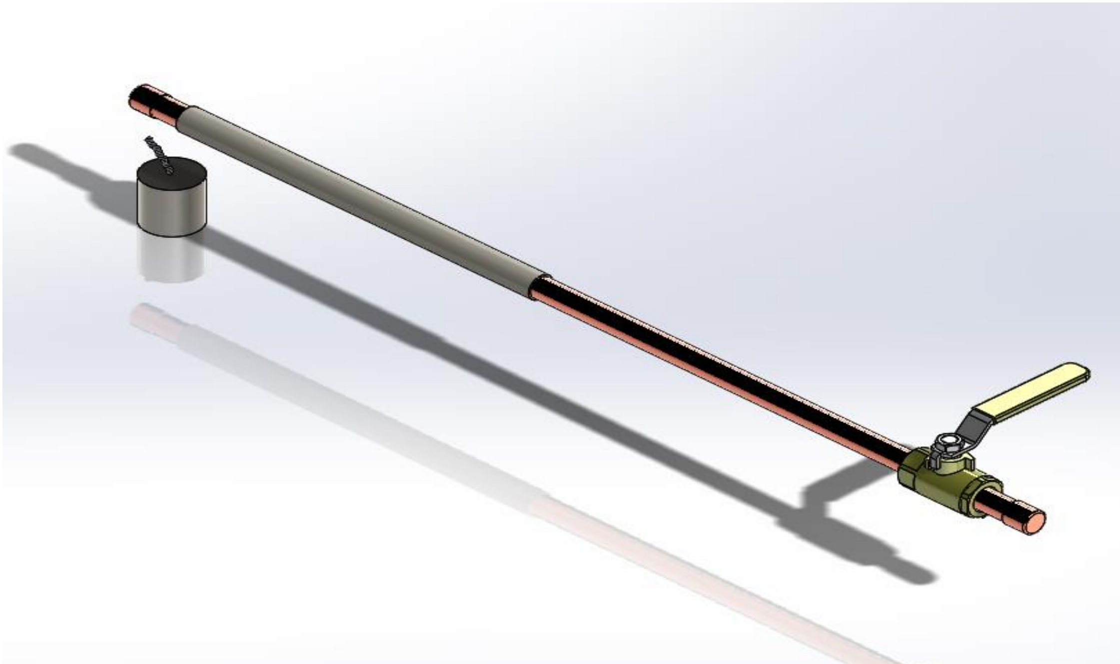


Figure 20. Heat pipe prototype

In this prototype, the team used all the materials listed in the bill of materials in Appendix C Table2. Most of the materials will come from HomCo Lumber and Hardware and Waltermart while the thermometer and automotive kit will be ordered from Amazon and ToolDiscounter respectively.

The test has shown that at -15psi, 10mL of water will be heat up from 24.5 degrees Celsius to 56.6 degrees Celsius in 10 minutes. Considering that the copper pipe will be used, which has a diameter of 0.65in., its area will be:

$$A = \frac{\pi}{4}(0.65^2) = 0.31in^2 = 0.000201m^2$$

And if the candle will be used, Q is 70W. Thus, *k* will be:

$$k = \frac{Q}{A}\left(\frac{\Delta L}{\Delta T}\right) \ (1)$$

Where,

k = thermal conductivity

Q = power from heat source

A = area

$\Delta L$ = change in length

$\Delta T$ = change in temperature [7]

$$k = \frac{70}{0.000201}\left(\frac{0.72}{32.1}\right)$$

$$k = 7{,}835\ W/mK$$

### 5.2.2 Full Design

As an overview, copper was the material chosen to be used as the main heat pipe material because of its high thermal conductivity while water was chosen as the cooling liquid. The following subsections will further discuss each component and more importantly how the decisions were made in choosing the best material.

#### *5.2.2.1 Heat pipe material*

In a cylindrical heat pipe, the heat transfer rate can be computed as given below:

$$Q = \frac{2\pi k L \Delta T}{\ln(r_o/r_i)} \quad (2)$$

where,

k = thermal conductivity

L = length of the pipe

$r_i$ = inside pipe radius

$r_o$ = outside pipe radius

One of the most crucial parameters is the nature of the material used in designing the heat pipes. It is important to understand that materials tend to differ in their thermal conductivity. In the equation, the thermal conductivity is directly proportional to the heat transfer rate. This means that materials with higher thermal conductivity transfer heat faster. In a work previously carried out by George Meyer for Celsia Inc., it has been mentioned that the materials typically used in heat pipes are copper, aluminum, and iron, and their thermal conductivities are 401, 205, and 80 W/mK, respectively [11]. The variations in the heat transfer rates of the three materials with change in temperature have been illustrated in Figure 21. A more extensive comparison has been provided in the later sections of the report.

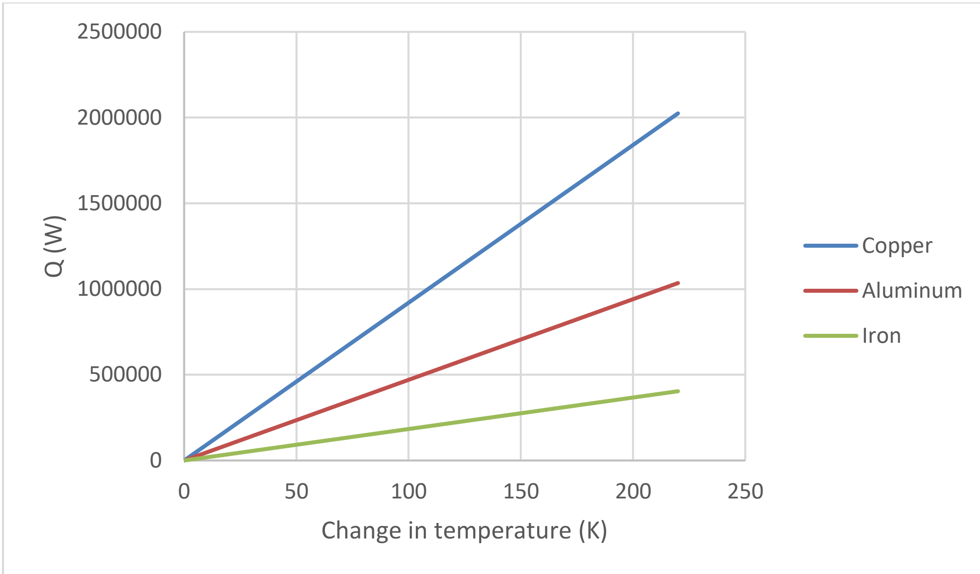



Figure 21. Comparison of Q using Cu, Al, and Fe

The thickness of the pipe is also an important design consideration. As the pipe thickness increases, its heat transfer rate decreases. In Figure 22, a copper pipe with a thermal conductivity of 401 W/mK, length of 1 m, inside radius of 0.0127 m, and a change in temperature of 50 K has been used to demonstrate this fact [11].

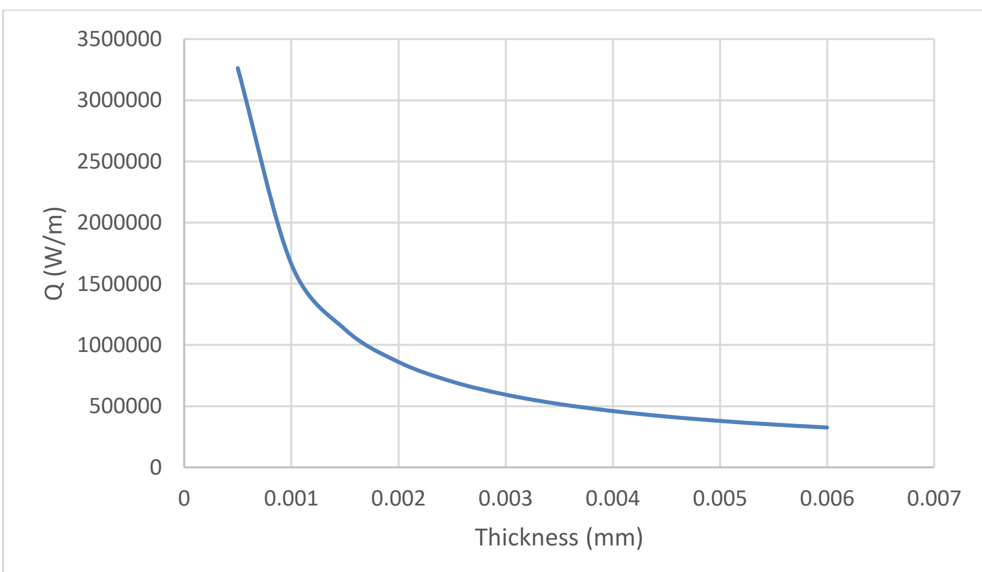



Figure 21. Effect of thickness on Q

Changes in temperature and length directly increase the heat transfer rate as shown in Figure 23 and 24, respectively. Hence, no matter how the temperature and the length are changed, their effects on the heat transfer rate will be the same regardless of the material and the dimension. For example, the effect of this change on three pipes made of different materials but having the same dimensions will be equal. The same logic applies for pipes made of similar materials but varying in dimensions.

For Figure 23, 0–250 K was employed as the change in temperature as it has been stated in the engineering requirement that the pipe should only be used at a maximum temperature of 200 degree Celsius. Since it is a heat chamber, the temperature will never fall below 0 degree Celsius. Based on these facts, it can be said that the minimum and maximum changes in temperature are 0 and 200°C, which are equivalent to 0 and 200 Kelvin, respectively. Moreover, since the relationship between the heat transfer rate and the change in temperature is a direct proportionality, the graph will hold true even on values greater than 200 K. The same principle applies to the change in length.

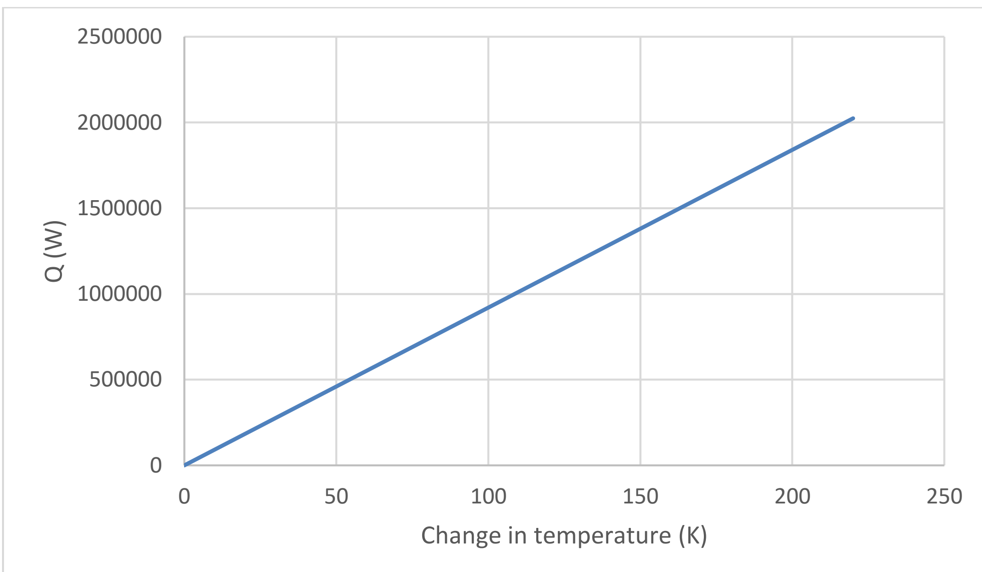



Figure 22. Effect of change in temperature on Q

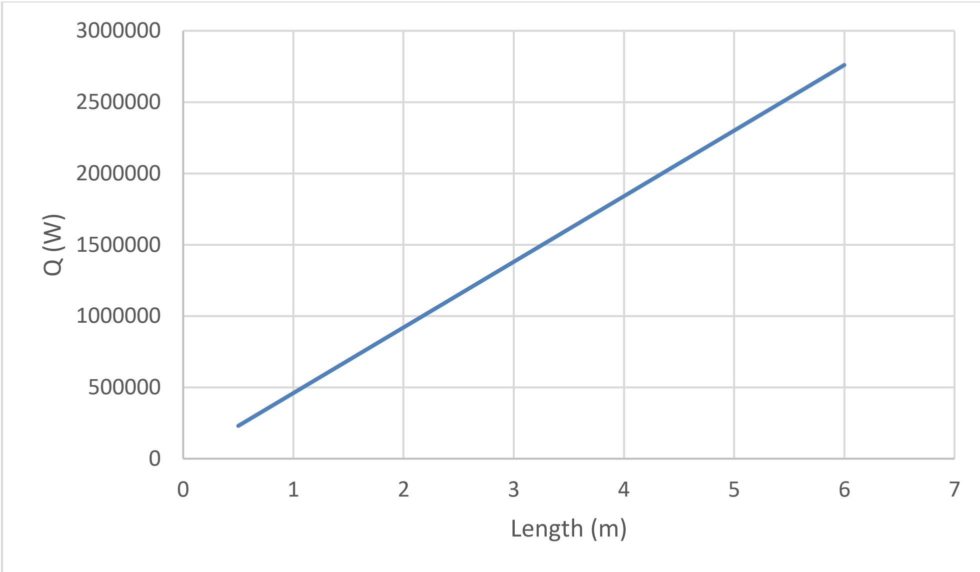



Figure 23. Effect of change in length on Q

Since the effect of each factor has already been established, it can be said that to increase the heat transfer rate, one must choose a material with high thermal conductivity. Also, one must select a thinner and longer pipe. However, there are cases in which the dimensions of the pipe available in the market are standardized as presented in Table 5 [12].

Table 5. Standardized pipe sizes.

| Size (in) | Inner radius (m) | Outer radius (m) | Size (in) | Inner radius (m) | Outer radius (m) |
|---|---|---|---|---|---|
| 1/4 | 0.0046228 | 0.006858 | 3 | 0.0389636 | 0.04445 |
| 3/8 | 0.0062611 | 0.0085725 | 3 1/2 | 0.0450596 | 0.0508 |
| 1/2 | 0.0078994 | 0.010668 | 4 | 0.0511302 | 0.05715 |
| 3/4 | 0.0104648 | 0.013335 | 5 | 0.0640969 | 0.0706501 |
| 1 | 0.0133223 | 0.0167005 | 6 | 0.0770255 | 0.0841375 |
| 1 1/4 | 0.017526 | 0.021082 | 8 | 0.1013587 | 0.1095375 |
| 1 1/2 | 0.020447 | 0.02413 | 10 | 0.127254 | 0.136525 |
| 2 | 0.0262509 | 0.0301625 | 11 | 0.1397 | 0.149225 |
| 2 1/2 | 0.0313563 | 0.0365125 | 12 | 0.1524 | 0.161925 |

Except for the radius, all other factors considered in computing the heat flux of the pipe directly contribute to it. Thus, it is important to know the exact effects. Figure 25 portrays the heat transfer rate for each standardized dimension by incorporating the different materials that can be used. As inferred from the graph, regardless of the size, the pipe made of copper will always have a higher heat transfer rate. Figure 26 further supports the claim by testing a 12 in pipe under varying changes in temperature by using the three materials. Therefore, the best material to be used is copper. The dimension will vary depending on other factors and limitations.

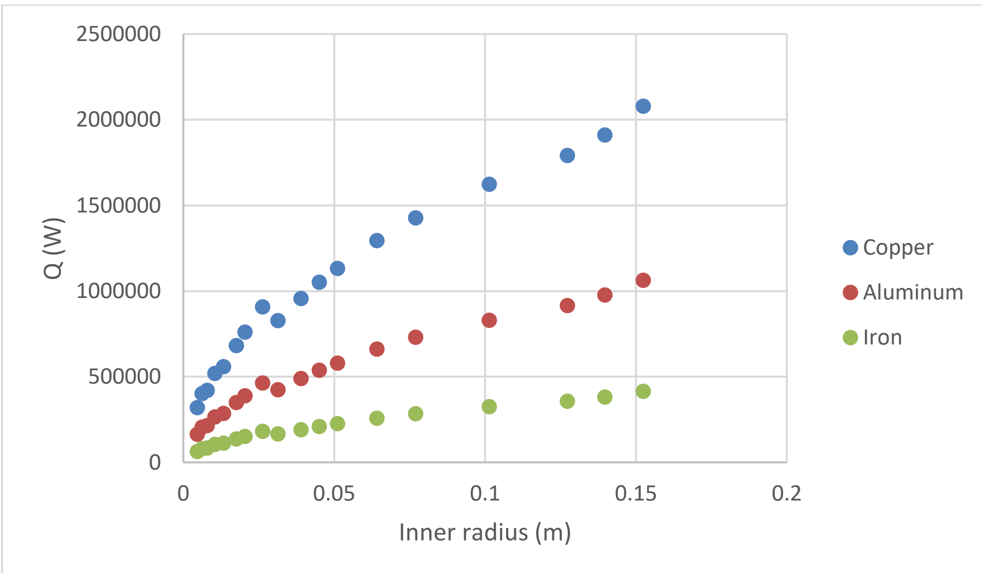



Figure 24. Q using standardized pipe size

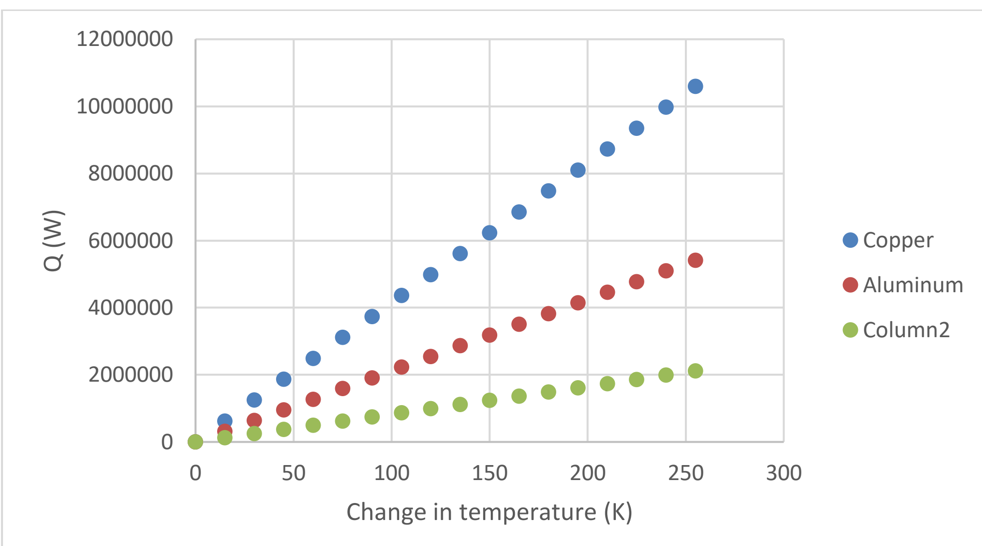



Figure 25. Q of a standard pipe made of different materials

Based on the Monotaro.ph, an online store for hardware material, the cost of a copper pipe compared to an aluminum and iron pipe is much lower [13]. We compared similar pipes, 8 inches in diameter and ¼ inches thickness as shown in Table 6.

Table 6. Cost of each material

| Material | Cost |
|---|---|
| Copper | \$5.99 |
| Aluminum | \$6.99 |
| Iron | \$8.99 |

### *5.2.2.2 Wick material*

The heat pipe considered in this project is made of copper with water as working liquid. The parameters used in this analysis are shown in Tables 7-9.

Table 7. Copper heat pipe parameters.

| **Copper Pipe data** | | | |
|---|---|---|---|
| total length | lt | 0.3 | m |
| inner radius | ri | 0.01 | m |
| Axial Angle | Ψ | 30 | Degree |
| thermal conductivity | λm | 394 | W/m C |

Table 8. Properties of Water as working fluid at 100.

| | | |
|---|---|---|
| Liquid density (ρl) | 958 | kg/m3 |
| Surface Tension (σ) | 0.00589 | N/m |
| Latent Heat (λ) | 2258000 | J/kg |
| Liquid Viscosity (μl) | 2.80E-04 | Ns/m2 |

Table 9. Compatible wick data.

| **Compatible Wick Type** | 250 mesh | |
|---|---|---|
| Wire diameter | 0.000045 | m |
| Layers | Single, double & Triple | |
| Wick length (Leffective) | 0.26 | m |
| Wick Permeability (Kwick) | 3.02E-11 | m2 |
| Wick Area (Awick) | 8.48E-06 | m2 |
| Pore size of wick (rc) | 2.00E-05 | m |

Heat pipes fluids are ranked by the Merit number which as shown in formula 1:

$$N = \frac{\rho * \sigma * \lambda}{\mu} (3)$$

Where is N is the merit number

$\rho$ is the density which is in $kg/m^3$

$\sigma$is the surface tension which is in N/m

$\lambda$is the latent heat which is in J/kg

$\mu$ is the liquid viscosity which is in $Ns/m^2$

Using the formula above, the computed Merit number at 100 degrees Celsius water id 4.55E+10. Moreover, in order to increase the efficiency of heat pipe, the pressure drop should be decreased, this can be achieved by reducing effective length and by increasing wick area, Table 10 and Figure 27 illustrate the effect of both while keeping the flow rate and wick material constant.

From this formula 2, we got the calculation:

$$\Delta P = \frac{m * \mu * Leffective}{\rho * Kwick * Awick} \ (4)$$

Where

m is the mass flow rate

u is the viscosity which is in $Ns/m^2$

$L_{effective}$ is the effective length of the wick which is in m

$\rho$ is the density which is in $kg/m^3$

$K_{wick}$ is the wick permeability $m^2$

$A_{wick}$ is the area of the wick $m^2$ [14]

Table 10. Pressure drop vs wick are and effective length.

| **Single Layer mesh wick** | **L Effective** | **Pressure Drop** |
|---|---|---|
| | 0.3 | 1027 |
| | 0.28 | 959 |
| | 0.26 | 890 |
| | 0.2 | 685 |
| **Double Layer mesh wick** | | |
| | 0.3 | 514 |
| | 0.28 | 479 |
| | 0.26 | 445 |
| | 0.2 | 342 |
| **Triple layer mesh wick** | | |
| | 0.3 | 342 |
| | 0.28 | 320 |
| | 0.26 | 297 |
| | 0.2 | 228 |

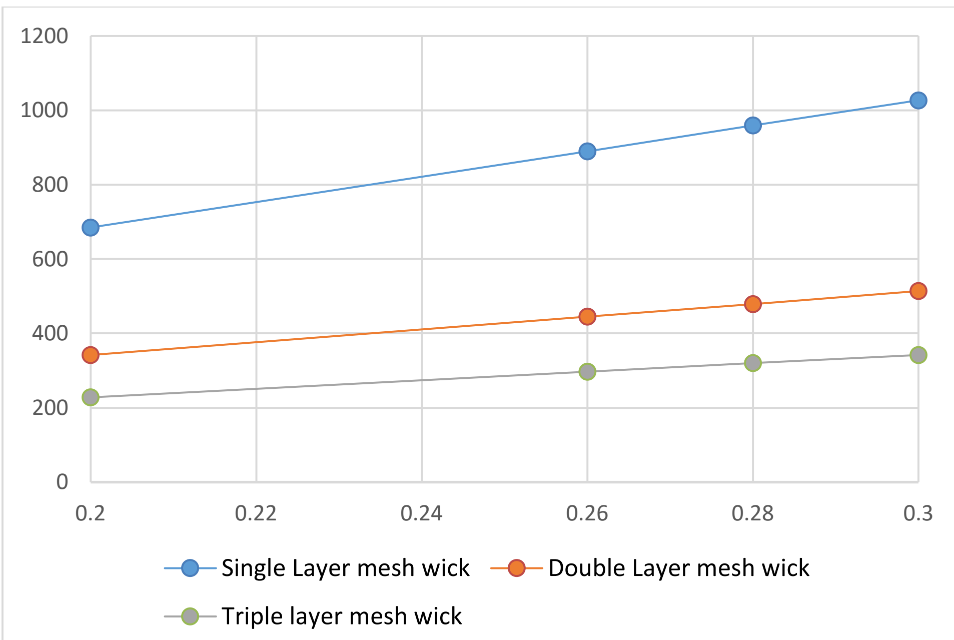



Figure 26. Pressure drop vs wick are and effective length.

Pressure drop decreases as we increase the wick area. Pressure drop decreases as we decrease the wick effective length. Table 11 and Figure 28 illustrate the effect of increasing wick area and decreasing effective length on heat transfer while keeping the flow rate and wick material constant;

$$Q = \frac{\frac{2 * Awick * Kwick}{rc * Leffective} * \rho * \sigma * \lambda}{\mu} \quad (5)$$

Where Q is the amount of heat transfer which is in W

rc is the pore size of the wick which is in m [16]

Table 11. Heat transfer vs wick area and effective length.

| **Single Layer mesh wick** | **L Effective** | **Amount of Heat Transfer** |
|---|---|---|
| | 0.3 | 1.29 |
| | 0.28 | 1.39 |
| | 0.26 | 1.49 |
| | 0.2 | 1.94 |
| | | |
| **Double Layer mesh wick** | | |
| | 0.3 | 2.59 |
| | 0.28 | 2.77 |
| | 0.26 | 2.99 |
| | 0.2 | 3.88 |
| **Triple layer mesh wick** | | |
| | 0.3 | 3.88 |
| | 0.28 | 4.16 |
| | 0.26 | 4.48 |
| | 0.2 | 5.83 |

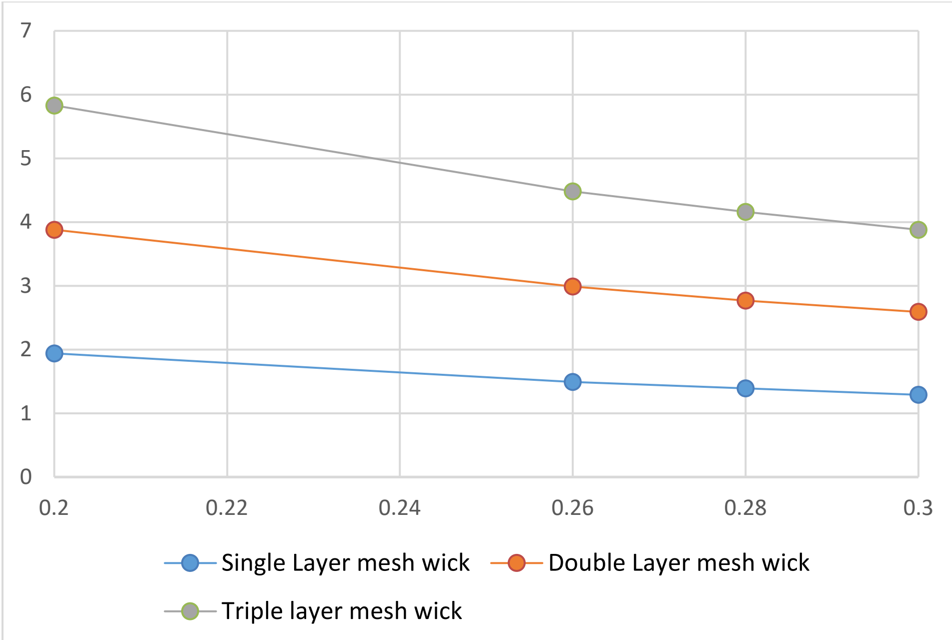



Figure 27. Heat transfer vs wick area and effective length.

Rate of heat transfer increases as we increase the wick area. Rate of heat transfer increases as we decrease the wick effective length. Table 12 and Figure 29 illustrate the effect of increasing wick permeability and while keeping all factors constant.

Table 12. Heat Transfer Vs Wick area and permeability

| **Single Layer mesh wick** | **K wick** | **Amount of Heat Transfer** |
|---|---|---|
| | 3.02E-11 | 1.29 |
| | 4.02E-11 | 1.72 |
| | 5.02E-11 | 2.15 |
| **Double Layer mesh wick** | | |
| | 3.02E-11 | 2.59 |
| | 4.02E-11 | 3.45 |
| | 5.02E-11 | 4.3 |
| **Triple layer mesh wick** | | |
| | 3.02E-11 | 3.88 |
| | 4.02E-11 | 5.17 |
| | 5.02E-11 | 6.46 |

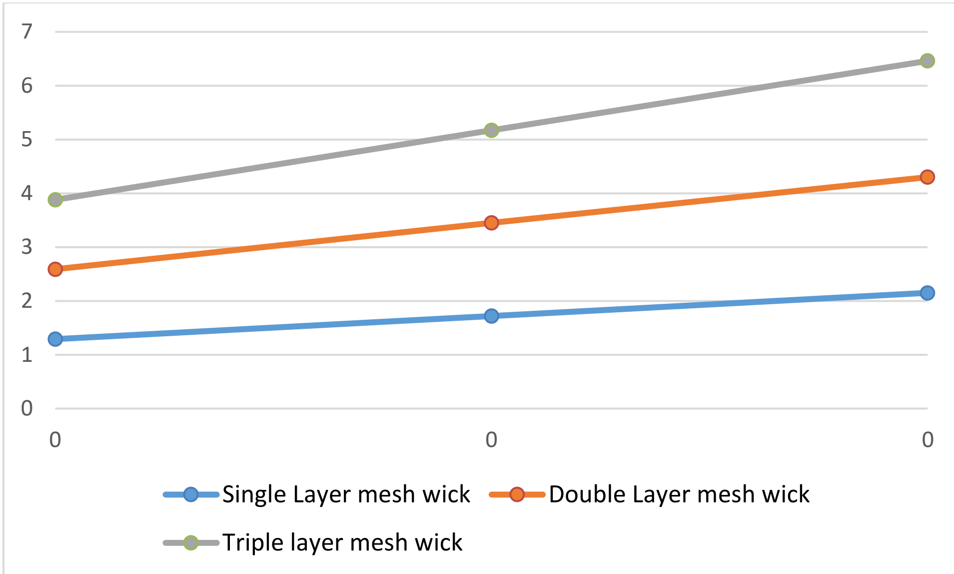



Figure 28. Heat Transfer Vs Wick area and permeability

#### *5.2.2.3 Working fluid*

The selection of the heat pipe determines its overall performance in terms of heat flux or transfer. Various types of heat pipes can be modified using forced convection to increase their performance. The design features of the pipes are responsible for their advantages and disadvantages. In addition to the material used and the dimensions of the pipe, the fluid also has an impact on the overall heat transfer rate. Fluids are graded according to the Merit number, and it is calculated as follows:

$$N_l = \frac{\rho_l \sigma \lambda}{\mu_l} \quad (6)$$

where,

$\rho_l$ = liquid density

$\sigma$ = surface tension

$\lambda$ = latent heat

$\mu_l$ = liquid viscosity [11].

High liquid density and latent heat are preferred as the fluid flow needed to transport the same energy is reduced. A high surface tension is also favored since it increases the pumping capability. However, for the liquid viscosity, a lower value is desired for lower liquid pressure drop [11].

The fluids that are typically used in heat pipes are water, ammonia, and methanol. To test which is the most suitable one, its Merit number was computed. The values of the properties were taken at room temperature, that is, 25 degrees Celsius, which is summarized in Table 13.

$$N_l = \frac{\rho_l \sigma \lambda}{\mu_l}$$

Merit number of water:

$$N_{l,water} = \frac{(997.0479\text{kg/m}^3)(808\text{kJ/kg})(0.072\text{N/m})}{0.000894\text{Pa}}$$

$$N_{l,water} = 64{,}881{,}721$$

Merit number of ammonia:

$$N_{l,ammonia} = \frac{(784.5\text{kg/m}^3)(548\text{kJ/kg})(0.\text{N/m})}{0.000207\text{Pa}}$$

$$N_{l,water} = 9{,}516{,}511$$

Merit number of methanol:

$$N_{l,methanol} = \frac{(786.75\text{kg/m}^3)(1160\text{kJ/kg})(0.02225\text{N/m})}{0.000566\text{Pa}}$$

$$N_{l,water} = 35{,}876{,}356$$

Among the three options, water has the highest Merit number; thus, it is the most suitable fluid.

Table 13. Thermophysical properties of water, ammonia, and methanol

| Fluid | Density ($kg/m^{3)}$ | Latent heat (kJ/kg) | Surface tension (N/m) | Viscosity (Pa) | Convective heat transfer coefficient ($W/m^2K$) |
|---|---|---|---|---|---|
| Water | 997.0479 | 808 | 0.072 | 0.000894 | 3000 |
| Ammonia | 601 | 132.1667 | 0.0248 | 0.000207 | 2555.218499 |
| Methanol | 786.75 | 1160 | 0.02225 | 0.000566 | 2553.50966 |

This can be further checked by computing the heat flux using the equation:

$$Q = hA\Delta T \ (7)$$

Where,

h = convective heat transfer coefficient

A = area

$\Delta T$ = change in temperature [7]

Looking at the equation, it can be already concluded that, when area and change in temperature are held constant, fluids with higher convective heat transfer coefficient will have higher heat transfer rate. The higher convective heat transfer coefficient of the three fluids in comparison is summarized in Table 13. To illustrate further, for a pipe with a theoretical area of $0.2\text{m}^2$ and is under 50K change in temperature, the heat transfer rate of the three fluids are:

$$Q = hA\Delta T$$

$$Q_{water} = \left(\frac{3000\text{W}}{\text{m}^2 K}\right)(0.5\text{m}^2)(50K) = 75{,}000W$$

$$Q_{ammonia} = \left(\frac{2555.218\text{W}}{\text{m}^2 K}\right)(0.5\text{m}^2)(50K) = 63{,}880.46W$$

$$Q_{methanol} = \left(\frac{2553.81\text{W}}{\text{m}^2 K}\right)(0.5\text{m}^2)(50K) = 63{,}837.74W$$

Thus, water must be chosen as the fluid for the heat pipe.

For the three fluids in comparison, we gathered data on their cost, summarized in Table 14, and we found out that water is the cheapest fluid [14]. Assuming that each fluid will be used in the same quantity, it can be concluded that water is the best fluid for this project. Moreover, water is the safest because it does not contain chemicals.

Table 14. Cooling fluid cost.

| Material | Cost per liter |
|---|---|
| Water | \$0.35 |
| Ammonia | \$0.434 |
| Methanol | \$0.73 |

#### *5.2.2.4 Pressure*

One of the major components that will be used in this project is a fluid. The liquid will be put into a heat pipe forming a contact with a thermally conductive strong surface transforms into a vapor by retaining heat from that surface. Vapor produced at this point moves along the heat pipe through the cold interface and corrects once again into a fluid and consequently discharging inactive heat.

This report will precisely analyze how the pressure changes the boiling point. It tries to explain how boiling point is a function of pressure. The input of the system is providing pressure and the output of the system is changing the boiling point. This analysis will help in designing phase to select the design and will help the team in manufacturing phase to manage the pressure with boiling point. As the boiling point with respect to pressure will examine in this report so it will clearly help the team to select the fluid accordingly in which pressure and boiling point will consider as well and selection of fluid is a designing phase.

Consider that the pressure $P_o$

$$P_o = 1\ atm = 100\ KPa$$

And the temperature $T_o$ is

$$T_o = 100^o C$$

And the heat of vaporization is

$$\Delta H_{vap} = 40.79\ \frac{kJ}{mol}$$

And the boiling temperature has assumed

$$T_B = 50^o C$$

And the equations to use is [15]

$$\ln\left(\frac{P_2}{P_1}\right) = -\frac{\Delta H_{vap}}{R}\left[\frac{1}{T_2} - \frac{1}{T_1}\right] \qquad (8)$$

In the above equation P2 is new pressure and P1 is atmospheric pressure, $\Delta H_{vap}$ is heat of vaporization, R is ideal gas constant, T1 is current boiling temperature, T2 is new boiling temperature. Another equation formation for finding the Vapor pressure and Temperature at boiling point is Clasius-Clapeyron equation [16]

$$T_B = \left(\frac{1}{T_o} - \frac{R \ln\frac{P}{P_o}}{\Delta H_{vap}}\right)^{-1} \qquad (9)$$

In the above equation $T_B$ is the new boiling temperature, R is the ideal gas constant, P is the new pressure, $P_o$ is the atmospheric pressure, and $\Delta H_{vap}$ is the heat of vaporization.

All the equations have defined already so now going to evaluate the pressure effect on the boiling point by taking the assumed values as the input data and find the new pressure and temperatures.

If for example, we wanted to find out the vapor pressure of water at 50 degrees Celsius

$$\Delta H_{vap} = 40.79 \frac{kJ}{mol}$$

$$T_2 = 100^o C$$

$$T_1 = 100 + 273.2 = 373.2\ K$$

$$T_2 = 50 + 273.2 = 323.2\ K$$

$$P_1 = 1\ atm = 760\ Torr$$

$$P_2 = (760)e^{\left\{\frac{-40.790^{-1}}{8.314\left\{\frac{1}{323.2}-\frac{1}{373.2}\right\}}\right\}} = 99.4\ Torr$$

Now we have seen that when the boiling point reduces to half, from 100 degrees to 50 degrees, then the required vapor pressure is 99.4 $Torr$ and before that it was 760 $Torr$. In the same way we can determine the boiling temperature by changing the applied pressure. Consider that

$$P_1 = 1\ atm = 760\ Torr$$

$$P_2 = 99.4\ Torr$$

$$T_1 = 100^o C$$

$$\Delta H_{vap} = 40.79 \frac{Kj}{mol}$$

Now putting the values again into the equation as

$$T_B = \left(\frac{1}{T_o} - \frac{R \ln \frac{P}{P_o}}{\Delta H_{vap}}\right)^{-1}$$

$$T_B = \left(\frac{1}{100} - \frac{8.314 \ln \left(\frac{99.4}{760}\right)}{40.79}\right)$$

$$T_B = 99.89^o$$

It proves that when the external pressure has reduced then the boiling point has reduced as well which means both are linking directly with each other. When the pressure reduces, boiling point also reduces and when the pressure increases boiling point also increases. With regard to of intermolecular forces, the boiling point characterizes the point at which the liquid molecules have sufficient thermal energy to conquer the different intermolecular attractions binding the molecules into the liquid. As such the boiling point is as well an indicator of the power of those attractive forces. The stronger the intermolecular attractive forces are, the harder it is for molecules to flee from the liquid and therefore the least is the liquid vapor pressure. The lower the vapor pressure of the liquid, the stronger the temperature needs to be so as to start boiling. Therefore, the stronger the intermolecular attractive forces are, the higher is the normal boiling point.

From the analysis it has found that boiling point varies directly when the pressure applied varies. It can conclude that both are interlink with each other, when the pressure is high boiling point is also high and when the pressure is low boiling point is also low and vice versa. This analysis will help the team to complete the designing of project by selecting such a liquid which has higher boiling point because when the external pressure will apply to the system its boiling point will reduce and the cooling effect cause by the liquid will mesmerize and liquid will evaporate, and in this way this analysis has helped the team performing the selection of liquid.

#### *5.2.2.5 Thermal conductance*

The heat pipe operation is based on the phase transition and characteristics of a fluid as a component to transfer heat with high efficiency. Generally, the heat pipe is a sealed container in the form of a tube that contains a wick lining in the inside wall [17]. The wick serves to transport the working fluid in the heat pipe from one end to the other via capillary action. The heat pipes are desirable due to the following advantages; high thermal transportation capability, changeable thermal flux density, constant temperature characteristics and excellent isothermal performance [17]. The advantages have increased the applications e.g. in spaceflight, computers and heat reclamation from waste smoke.

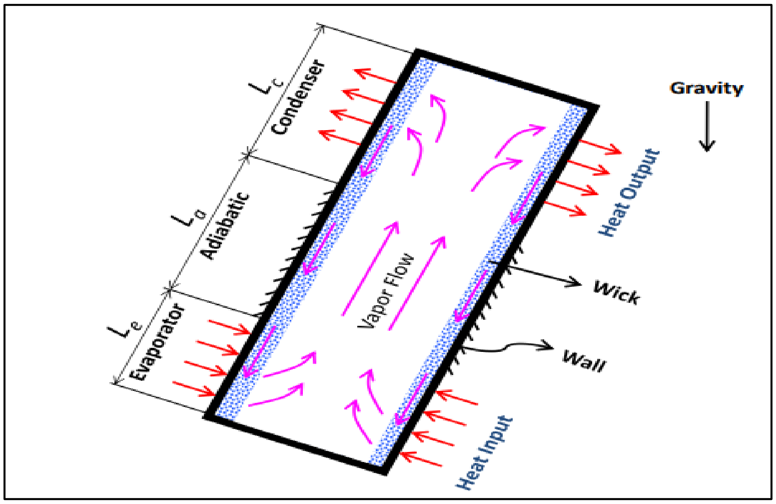



Figure 29. The schematic of the heat pipe

The purpose of the experiment will be to assess the operation of fins in a general heat pipe system. The experiment will compare the results for the materials used for creating fins.

The experiment will be carried in two steps; an analytical solution and a numerical simulation. The key aspect will be to compare the heat characteristic of two materials that can be used to create fins in a heat pipe. The analytical solution in the experiment will entail the determination of the thermal response time of a high conductivity metal such as copper-water heat pipe inserted in hot and cold water. The data collected during the analytical solution was compared to the response of a copper rod with the same dimensions, i.e., similar length and diameter. The numerical solution would permit the analysis of a heat pipe that would have a wick and the working fluid. The analysis would consider the source of heat as a flexible heater of width 45 mm wrapped to one end of the heat pipe. The other end, i.e., the uncovered end, would be exposed to the ambient air serving as the condenser hence it would be cooled by free convection.

The results calculated in the analytical solution will be compared with results from numerical simulation. The initial phase will entail the derivation of the relevant differential equation. Once the equation had been derived, the simulation code was created in MATLAB and run to produce the resultant graphs. The graphs would be used to compare the result of the experiment.

Consider a rod of 20 cm in diameter and 25 cm in length where the heated end will be 100 ºC while the temperature of ambient air would be 30 ºC.

Assumptions

1. Temperature of ambient air will be constant at 30 ºC
2. The pressure of the system will also be maintained at constant.
3. The measurements were similar for the two materials

The temperature at the free end of the rod can be determined as:

The specific heat of copper will be k = 330 W/mk

The specific heat of steel will be k = 49 W/mk

Consider h = 7 W/m$^2$k

$$d = 2\,cm = 2\,x\,10^{-2}\ m$$

$$L = 25\,cm = 0.25\ m$$

$$T_o = 100^o C$$

Perimeter

$$\pi d$$

$$\pi d = \pi\,x\ 2\,x\,10^{-2}\ m = 0.0623\,m$$

Area

$$\frac{\pi}{4} d^2$$

$$\frac{\pi}{4} d^2 = \pi\ x\,(2\,x\,10^{-2})^2 = 3.1415\ x\,10^{-4}\,m^2$$

The boundary conditions in this case will be as expressed below:

At x = 0, $\theta = \theta_o$

$$\theta_o = T_o - T_f \tag{10}$$

$$\theta_o = T_o - T_f = 100 - 30 = 70^O\ C$$

$$\text{At } x = 0, \frac{d\theta}{dx} = \theta_o$$

Using analytical solution, the heat flow for the copper fins can be calculated using the expression below [7]:

Copper at = 330 W/mk

$$m = \sqrt{\frac{hP}{kA}} \tag{11}$$

$$m = \sqrt{\frac{hP}{kA}} = \sqrt{\frac{7 \ x\ 0.06283}{330 \ x\ 3.1415 \ x\ 10^{-4}}} = 2.05968 \ m^{-1}$$

The temperature distribution along the copper fins would be obtained by using the equation below [14]:

$$\frac{\theta}{\theta_o} = \frac{\cosh m(L - x)}{\cosh mL} \tag{12}$$

At the end of the fin x = L,

$$\frac{\theta}{70} = \frac{1}{\cosh mL}$$

$$\theta = 61.645^o\ C$$

Similarly, the temperature distribution along the steel fins would ultimately be calculated by replacing values in equation (5) below;

Steel at k = 49 W/mk

$$m = \sqrt{\frac{hP}{kA}} = \sqrt{\frac{7 \ x\ 0.06283}{49 \ x\ 3.1415 \ x\ 10^{-4}}} = 5.345 \ m^{-1}$$

$$\frac{\theta}{\theta_o} = \frac{\cosh m(L - x)}{\cosh mL}$$

At the end of the fin x = L,

$$\frac{\theta}{70} = \frac{1}{\cosh mL}$$

$$\theta = 34.41^o\ C$$

Table 15. Changes in the temperature along the fins

| Material | Initial Temperature (ºC) | Final Temperature (ºC) |
|---|---|---|
| Copper | 100 | 61.645 |
| Steel | 100 | 34.41 |

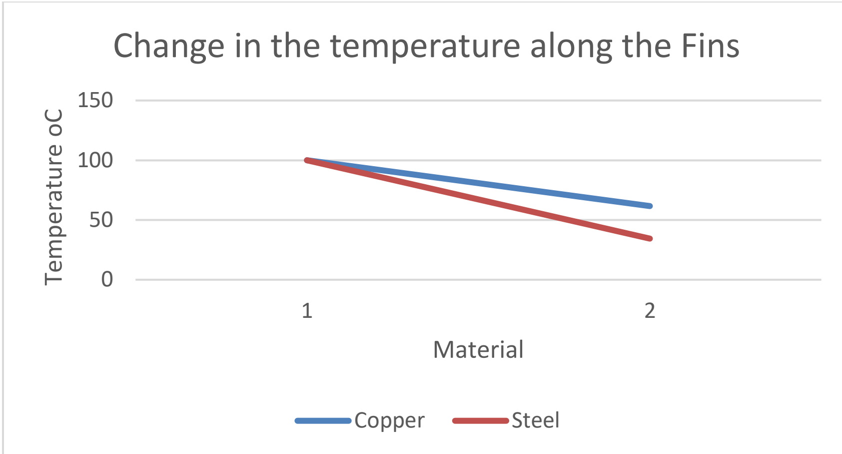



Figure 30. Change in the temperature along the fins

For the numerical computation of the data MATLAB was used. The solution will be obtained via the use of a differential equation with regards to the fins as expressed below;

$$\frac{d^2\theta}{dx^2} - m^2\theta = 0$$

For the steel rod, m = 2.05968

$$\frac{d^2\theta}{dx^2} - (2.05968)^2\theta = 0$$

$$\frac{d^2\theta}{dx^2} - 4.24222\theta = 0$$

For the steel rod

$$\frac{d^2\theta}{dx^2} - (5.345)^2\theta_1 = 0$$

$$\frac{d^2\theta}{dx^2} - 28.569\theta_1 = 0$$

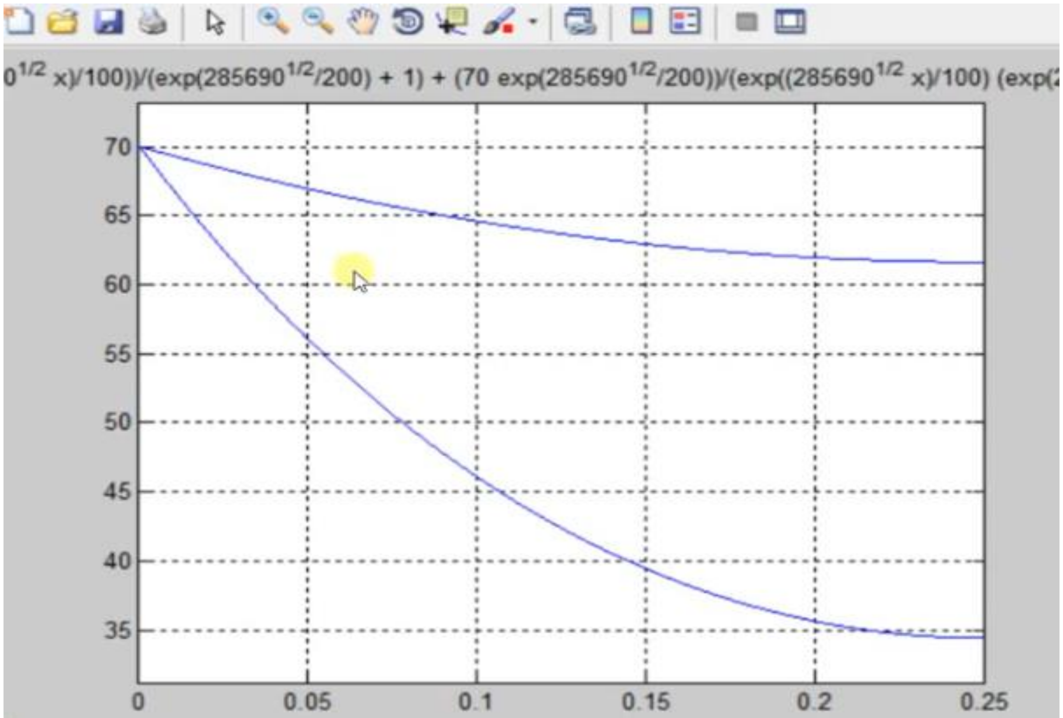
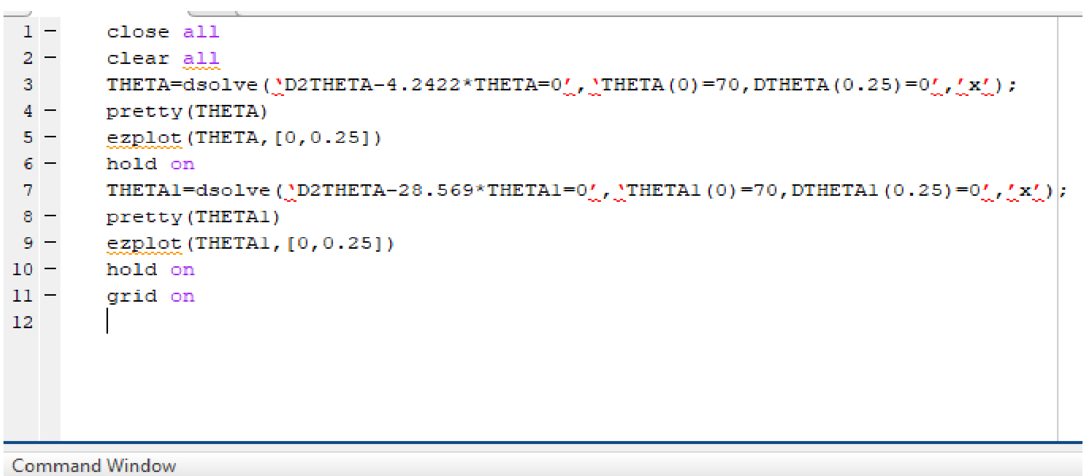



Figure 31. The graph illustrating the change in the temperature of the two rod.



```
close all
clear all
THETA=dsolve('D2THETA-4.2422*THETA=0','THETA(0)=70,DTHETA(0.25)=0','x');
pretty(THETA)
ezplot(THETA,[0,0.25])
hold on
THETA1=dsolve('D2THETA-28.569*THETA1=0','THETA1(0)=70,DTHETA1(0.25)=0','x');
pretty(THETA1)
ezplot(THETA1,[0,0.25])
hold on
grid on
```



Figure 32. MATLAB Code.

The result from the analytical solution illustrate that the final temperature for copper was $61.645^{o}C$ while that of steel was $34.41^{o}C$. The analytical result illustrates that steel is a better conductor than copper. The resultant graph illustrates that the temperature along the rod was decreasing. The decrease in the temperature was linear. Similarly, the results from the numerical simulation illustrate that the temperature decrease along the rod. Contrary to the analytical solution the decrease in the temperature was exponential.

# 6 PROPOSED DESIGN – First Semester

After the implementation of the first prototype, the team found out that the glass can be can be a better alternative for copper to get a higher heat flux. In this project, quartz glass heat pipe will be used as shown in Figure 34 It is made at least 99.9% silica. It has high melting point that it can be used in temperatures of up until 1200 degrees Celsius since its softening point is not until 1683 degrees Celsius [19]. It has 25mm as outer diameter and 22mm as inner diameter. The length is at 2.5ft with 0.8ft extension.

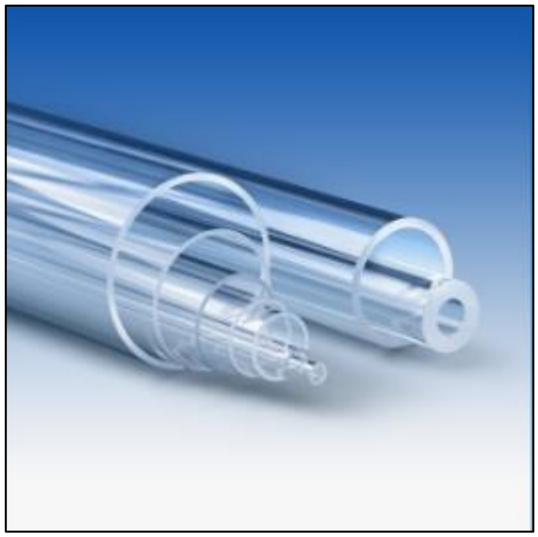


Figure 33. Quartz glass heat pipe.

Also, heater band can be used as an alternative heat source instead of candle since it does not involve open flames as shown in Figure 35. It has a nozzle temperature of 537 degrees Celsius. It also has at least 275 watts at 120 volts.

Figure 34. Heater Band.

## 6.1 Prototype Implementation

From the previous discussion, it was stated that only the heat pipe material and the heat source will be changed from the precious design. This means that the rest of the materials used will stay the same. Shown in Appendix C Table.3 is the bill of materials for full design. The glass pipe will be outsourced from TechnicalGlass.com while the heater band will be from Omega.com. Also, we will use 4-way valve instead of 2-way valve as shown in Figure 36.

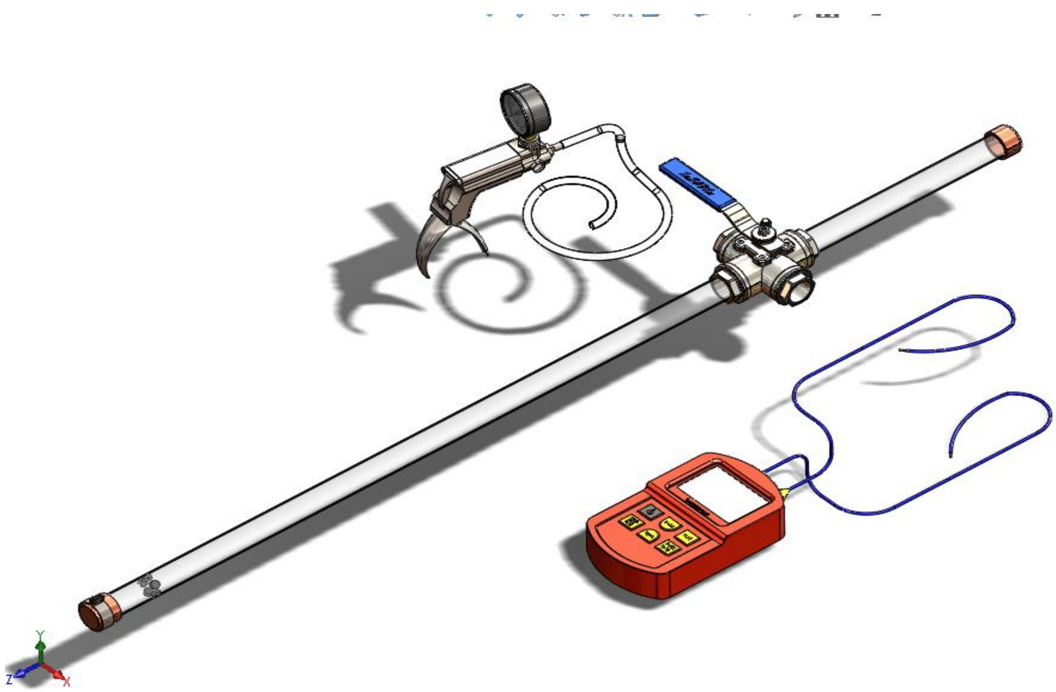


Figure 36. Full Design Assembly.

## 6.2 Proposed Design Implementation

For the full design, the team has allotted 16 weeks for its completion as shown in the Gantt chart in Table 16. This will be done from the 27th of August 2018 to the 14th of December of the same year. The first week will be allotted for the finalization of the design. The team needs to be sure that all aspects of the project was considered since most of the acquisition of some of the materials will be done online. This is to ensure that all parts. Canvassing of the materials was also put in the first week because although the team has already established the sites where the materials will be bought, the availability of the desired specifications is still subject for change. In the second week will be the placement of orders in the online shop. There are three weeks allotted for the waiting of orders to arrive since some of the materials will be from an online shop. The shipping is very variable since it will depend on the courier.

When the orders arrive, the team can now start to manufacture the full design. Two weeks is allotted for this to give way for some modifications on the material and some room for trial-and-error. The next stage will be the testing. The team allotted a week for this. Then there will be two sessions for the improvement of the full design. This is to ensure that the maximum efficiency was reached. The results of the first testing will be used to improve the next version. Each improvement session will be followed by a testing. Finally, two weeks was allotted to make the write-up for the project and edit it in case there was a modification from the original design.

The team decided to plan the implementation per week to cover all uncontrolled circumstances like scheduling among the members, other people using the laboratory, etc. As shown also in the Gantt chart, the project will finish two weeks earlier than schedule. This two weeks will be an allowance in case the orders arrive late or if the team will need additional week for improvement and testing.

Table 16. Gantt chart.

| | A | September | | | | October | | | | | November | | | | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| finalization of design | ■ | | | | | | | | | | | | | | | |
| canvassing of materials | ■ | | | | | | | | | | | | | | | |
| placing of orders | | ■ | | | | | | | | | | | | | | |
| waiting for orders to arrive | | | ■ | ■ | ■ | | | | | | | | | | | |
| initial implementation of Full design | | | | | | ■ | ■ | | | | | | | | | |
| improvements on the Full design | | | | | | | | | ■ | | ■ | | | | | |
| testing the full design | | | | | | | | ■ | | ■ | | ■ | | | | |
| write-up | | | | | | | | | | | | | ■ | ■ | | |

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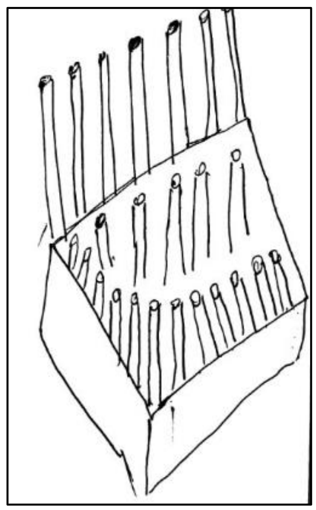
# 7 Appendices

## 7.1 Appendix A: Design Considered

### 7.1.1 Design #6: Forged Fins

Forged fins heat sink is design in which fins makes in specific pattern and each pattern repeats over the span. This type of heat sink is famous for specialized designs because these sinks develops according to the required shape and design, one of the design is showing in the figure.



Appendix Figure 1. Forged Pins Heat Sink

**Typical Benefits:**

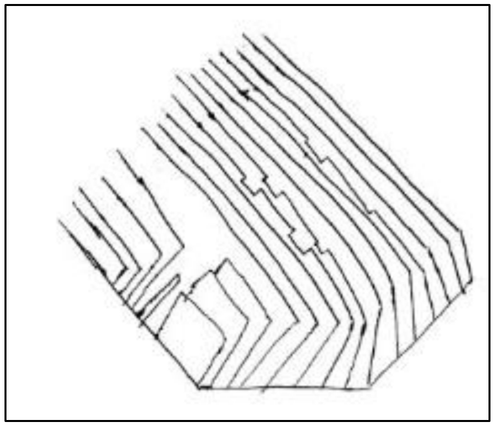
Fin design in many shapes (pin, square, oval, etc.)

**Potential Pitfalls:**

Usually reserved for higher volume products as tooling is expensive.

### 7.1.2 Design #7: Machined Fins

These are smaller type of heat sinks which formed from both aluminum and copper. These type of heat sinks are mostly common to use for electronic machines in which they just need to absorb small amount of heat energy and provide low level of cooling. These heat sinks are common in personal computers and showing in the following figure.



Appendix Figure 2. Machined heat Sink

**Typical Benefits:**

High thermal conductivity

Complicated designs OK

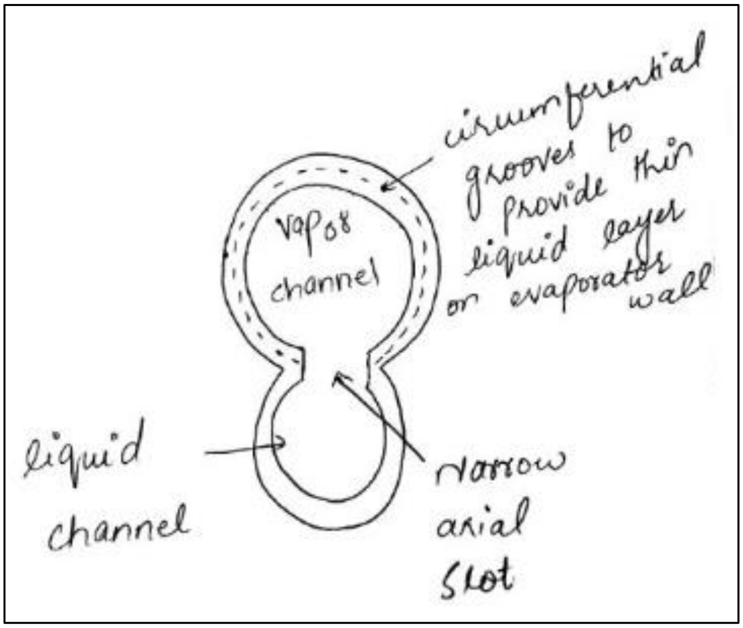
**Potential Pitfalls:**

None, other can cost.

Not good for high volume due to production time.

### 7.1.3 Design #8: "Mono-groove" Design

These type of heat sinks are common to use for aerospace machines where condensed form of cooling is requiring keeping the machines workings. In this type of heat sinks, liquid layers are present to provide the quick cooling without getting more heat from other sources. Mono-groove heat sink is showing in the following figure.




Appendix Figure 3. “Mono-groove” Heat Sink

**Typical Benefits:**

It has a large single groove that provides

Relatively unrestricted longitudinal flow.

Liquid is distributed on the evaporator wall

By means of a secondary wick consisting of small

Circumferential grooves or screen

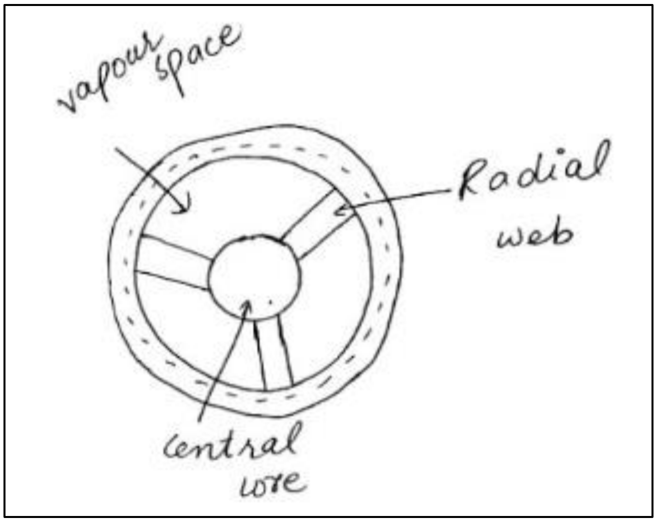
**Potential Pitfalls:**

It has encountered difficulties during early

Shuttle testing.

### 7.1.4 Design #9: Composite Wicks

This design has the grooves as well in the radial web and cause the generate the cooling quickly in the system. Composite wicks use the radial shaped outer body with the liquid in it and circled body which cause the heat sink to absorb more heat in short period of time.




Appendix Figure 4. Composite Wick Heat Sink

**Typical Benefits:**

More capacity can be obtained by using more layers of screen,

To increase the wick flow area.

**Potential Pitfalls:**

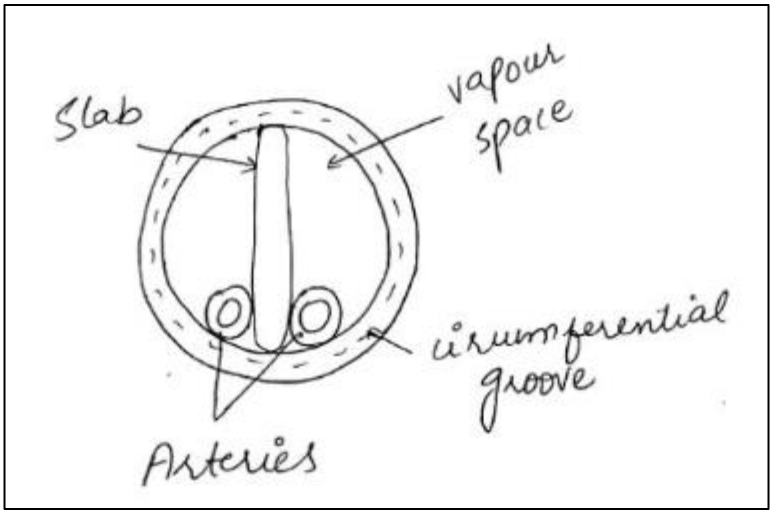
Because the wick must be assembled of relatively fragile materials,

Care is required in building such a pipe, and no two supposedly identical

Pipes will perform in exactly the same manner.

### 7.1.5 Design #10: Diode Heat Pipes

Diode heat pipes are considering to be the most advance form of heat sinks, in this kind of heat sinks there is no reverse flow, which means the heat will not flow back to the system once it will sink by the diode pipe. In diode pipe, heat sinks through the pipe and stays remains inside the pipe and it can see in the following figure.




Appendix Figure 5. Diode Heat Pipes

**Typical Benefits:**

A constant-conductance heat pipe can be modified so that

Operation occurs normally in one direction

**Potential Pitfalls:**

When an attempt is made to transfer heat in the other, "wrong" direction, resulting in a diode action.

## 7.2 Appendix B: Pugh Chart

Appendix Table 1. Pugh Chart

| Concept / Criteria | Ex-truded | Die cast | Bon-ded | Skived | Fin pack and zipper fins | Forged fins | Ma-chined fins | Mono groove | Com-posite wicks | Diode heat pipes |
|---|---|---|---|---|---|---|---|---|---|---|
| Durability | + | - | S | S | + | - | + | S | D | - |
| Reliability | - | + | + | + | S | - | - | - | D | + |
| Manufacturable | S | - | - | + | S | S | - | S | D | S |
| Safety | S | S | S | S | S | S | S | S | D | S |
| Ease of Assembly | - | + | + | - | - | + | - | + | D | - |
| Variability | - | + | S | + | + | - | + | - | D | - |
| Easy to Measure | - | S | + | + | - | + | + | S | D | S |
| ∑ + | 1 | 3 | 3 | 4 | 2 | 2 | 3 | 1 | D | 2 |
| ∑ - | 4 | 2 | 1 | 1 | 2 | 3 | 3 | 2 | D | 2 |
| ∑ S | 2 | 2 | 3 | 2 | 3 | 2 | 1 | 4 | D | 3 |

## 7.3 Appendix C: Bill of Materials

Appendix Table 2. BOM for prototype

| Bill of Materials | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Team | | | Heat Pipe - Team 3 | | | | |
| **Part #** | **Part Name** | **Qty** | **Functions** | **Material** | **Dimensions** | **Cost** | **Link to Cost estimate** |
| 1 | copper pipe | 1 | vessel | copper | 2 feet | $4.78 | HomCo Lumber & Hardware @flagstaff |
| 2 | copper caps | 2 | cap | copper | ID= 0.5in , OD=0.63 | $1.38 | HomCo Lumber & Hardware @flagstaff |
| 3 | valve | 1 | control | copper/cuivre | 1/2 in | $15.99 | HomCo Lumber & Hardware @flagstaff |
| 4 | disconnected clip | 1 | clip | copper/cuivre/cobre | 1/2 in | $1.99 | HomCo Lumber & Hardware @flagstaff |
| 5 | foam pipe insulation | 1 | insulation | foam | 70 in | $3.29 | HomCo Lumber & Hardware @flagstaff |
| 6 | wire trivet | 1 | we used it as stand | n/a | 7 in diameter (17.6 cm) | $4.72 | Walmart |
| 7 | ms coasters | 1 | we used it as stand | n/a | | $5.14 | Walmart |
| 8 | utensil holder | 1 | we used it as stand | n/a | 11.8 cm * 11.8 cm * 20 cm | $5.84 | Walmart |
| 9 | candle | 1 | heating source | n/a | n/a | $0.50 | Walmart |
| 10 | BRS Torch plumber kit | 1 | to flux the copper cap with the pipe | n/a | n/a | $22.99 | HomCo Lumber & Hardware @flagstaff |
| 11 | LCD thermoemeter w' thermocouple wires | 1 | measure temperature | n/a | n/a | $24.79 | Amazon |
| 12 | silverline elite automotive kit | | to vacuum pressure | n/a | n/a | $49.95 | ToolDiscounter |
| 13 | an extension copper pipe | 1 | extension | copper | 1/4 in | FREE | HomCo Lumber & Hardware @flagstaff |
| 14 | syringe | 1 | to add and measure fluids | plasic | n/a | FREE | from our client |
| 15 | Water | 1 | cooling fluid | Water | 1 liter | $0.35 | Walmart |
| **Total Cost Estimate:** | | | | | | $141.71 | |

Appendix Table 3. BOM for full design

| Bill of Materials | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Team | | | Heat Pipe - Team 3 | | | | |
| **Part #** | **Part Name** | **Qty** | **Functions** | **Material** | **Dimensions** | **Cost** | **Link to Cost est.** |
| 1 | glass pipe | 1 | vessel | glass | ID= 22mm, OD= 25mm, L= 2.5ft | $23.00 | Technical glass products |
| 2 | copper caps | 2 | cap | copper | ID= 22mm , OD=26mm | $1.38 | HomCo Lumber & Hardware @flagstaff |
| 3 | 4-way valve | 1 | control | copper/cuivre | 22.1 mm | $15.99 | HomCo Lumber & Hardware @flagstaff |
| 4 | disconnected clip | 1 | clip | copper/cuivre/cobre | 1/2 in | $1.99 | HomCo Lumber & Hardware @flagstaff |
| 5 | wire trivet | 1 | stand | n/a | 7 in diameter (17.6 cm) | $4.72 | Walmart |
| 6 | ms coasters | 1 | stand | n/a | n/a | $5.14 | Walmart |
| 7 | utensil holder | 1 | stand | n/a | 11.8 cm * 11.8 cm * 20 cm | $5.84 | Walmart |
| 8 | heater band | 1 | heating source | n/a | w= 1.35in | $169.00 | Omega |
| 9 | LCD thermoemeter w' thermocouple wires | 1 | measure temperature | n/a | n/a | $24.79 | Amazon |
| 10 | silverline elite automotive kit | 1 | to vacuum pressure | n/a | n/a | $49.95 | ToolDiscounter |
| 11 | an extension glass pipe | 1 | extension | coppper | L= 0.8ft, ID= 22mm. OD= 25mm | $9 | Technical glass products |
| 12 | cotton cloth | 1 | wick | cotton | 3 yards | $17.97 | Joann Fabric store @Flagstaff |
| 13 | Water | 1 | cooling fluid | Water | 1 liter | $0.35 | Walmart |
| 14 | Ammonia | 1 | cooling fluid | Ammonia | 1 liter | $0.43 | ng-tech |
| 15 | Methanol | 1 | cooling fluid | Methanol | 1 liter | $0.73 | ng-tech |
| 16 | timer | 1 | to keep time | n/a | n/a | $5 | Amazon |
| 17 | syringe | 1 | to add and measure fluids | plastic | n/a | FREE | Got it from our client |
| **Total Cost Estimate:** | | | | | | $335.28 | |