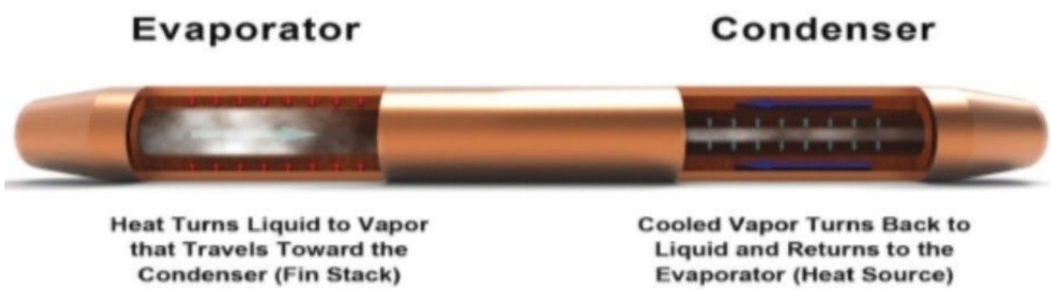
# *“SIMULATION OF HEAT PIPE”*

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# 1. **Introduction**

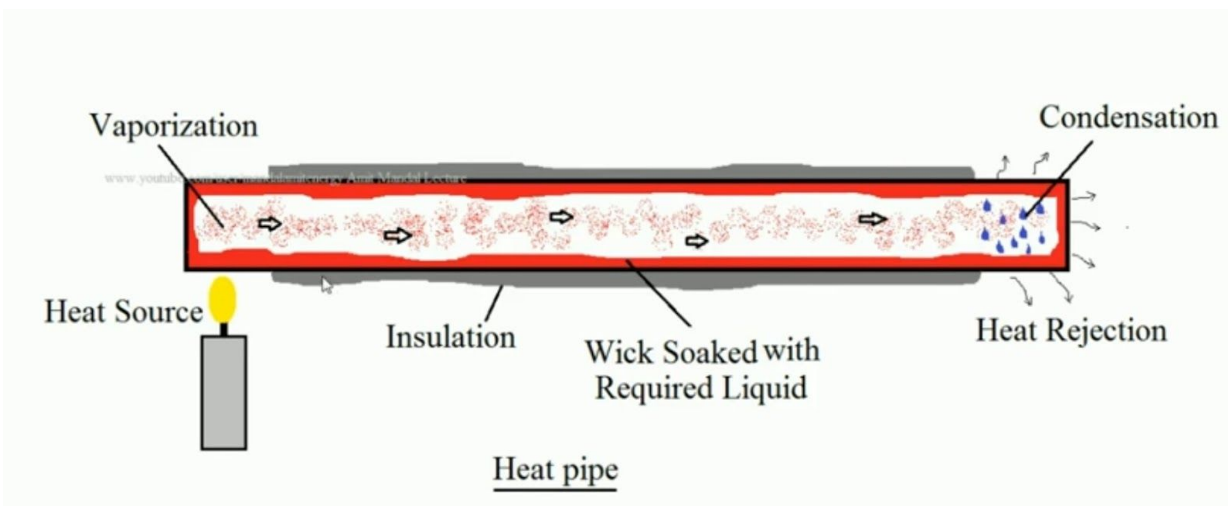
Simulations are used widely to demonstrate some mechanisms to teach basic engineering principles. Our project is to demonstrate the simulation of heat pipe. A heat pipe is a pipe filled with a liquid and wicking material that transfers heat much faster than a stand alone pipe because it uses conduction and convection as opposed to conduction alone. Heat pipes are commonly used in electronics and space applications, where rapid heat transfer to remove heat from the system is necessary.

## Aim:

Our team has been tasked with designing and simulating a heat pipe demonstration unit with the help of Ansys software. We will use various different fluids, wicking materials, and pressures to test the efficiency of the heat pipe and create an experiment to analyze the parameters.

## Overview of the heat pipe:

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. Generally speaking heat pipes is consists of a shell or (wall), a wick and a some amount of the working fluid.
Three sections can be characterized in a heat pipe:
1. Evaporator
2. Condenser
3. Adiabatic section.
Evaporator part sinks the heat from high temperature side and convert the working fluid to vapor inside. The vapor starts flowing through the adiabatic part and then condensate at the condenser side, the latent heat of condensation will be released to a low temperature source. The condensed liquid then returns back to the evaporator through the wick by the virtue of capillary driving force.



# Design parameters and Factors affecting heat pipe performance:

## (i) Material used for container and dimensions:

Container is a shell or tube to contain the working fluid and wick within itself. It is made up of different types of materials like copper, aluminium, steel, tungsten, titanium. Material used for container must have higher thermal conductivity and must be compatible with the working fluid used. Generally copper is used for higher thermal conductivity approximately 400 w/m° C and low cost as compared to other materials.

Thermal conductivity has relation with length of heat pipe. It may go upto 100000w/m K in comparison to high thermal conductive material like copper of 400w/m K. Thickness also affects the performance of heat pipe by offering thermal resistance. Suppose we consider length of pipe 1000 mm then the thickness of pipe and wick should not be more than 2mm.

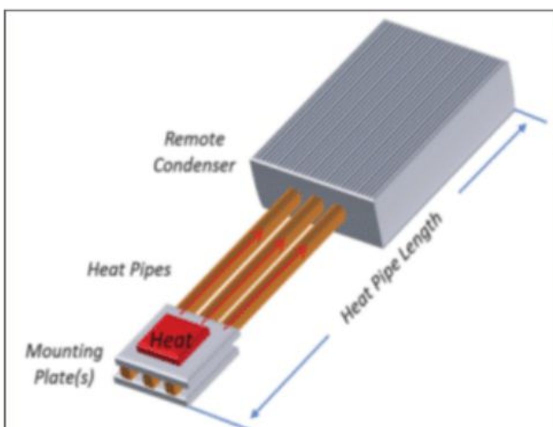
Casing material should have the following characteristics

• Compatibility (both with working fluid and the external environment)

• Strength-to-weight ratio

• Thermal conductivity

• Ease of fabrication, including weldability, machinability and ductility.




| Heat Pipe Length (mm) | Effective Thermal Conductivity (W/m.K) |
|---|---|
| 75 | 6,600 |
| 100 | 11,000 |
| 150 | 19,900 |
| 200 | 28,700 |

Note: heat load = 25 W per 6 mm diameter heat pipe.

Figure 2. Measured heat pipe effective thermal conductivity as function of length.

## (ii) Properties of Working Fluid:

Characteristics of working fluid is the most important factor of heat pipe. The properties will affect the ability to transfer heat and compatibility with the case and wick material.

Some things are to be considered when working fluid is selected.

- Compatibility with wick and wall materials.
- Good thermal stability
- Wettability of wick and wall materials
- Vapor pressures not too high or low over the operating temperature range
- High latent heat
- High thermal conductivity
- Low liquid and vapor viscosities
- High surface tension

Basically working fluids like **water, nitrogen, ammonia, methanol, ethanol** are used when heat pipe is used in **low temperature** operating range. For **high temperature** ranges fluids like **liquid sodium, lithium, cesium, potassium** are used. Impurities in working fluid reduce the overall performance of heat pipe.
To measure the overall effectiveness of heat pipe, a mathematical expression termed L

Liquid transport factor (N) = $\frac{\rho\sigma\lambda}{\mu}$

Where ρ is density of fluid, σ is the surface tension in fluid, and μ is dynamic viscosity of fluid.

| Working Fluids | Melting Point, K at 1 atm | Boiling Point, K at 1 atm | Useful Range, K |
|---|---|---|---|
| Helium | 1.0 | 4.21 | 2–4 |
| Hydrogen | 13.8 | 20.38 | 14–31 |
| Neon | 24.4 | 27.09 | 27–37 |
| Nitrogen | 63.1 | 77.35 | 70–103 |
| Argon | 83.9 | 87.29 | 84–116 |
| Oxygen | 54.7 | 90.18 | 73–119 |
| Methane | 90.6 | 111.4 | 91–150 |
| Krypton | 115.8 | 119.7 | 116–160 |
| Ethane | 89.9 | 184.6 | 150–240 |
| Freon 22 | 113.1 | 232.2 | 193–297 |
| Ammonia | 195.5 | 239.9 | 213–373 |
| Freon 21 | 138.1 | 282.0 | 233–360 |
| Freon 11 | 162.1 | 296.8 | 233–393 |
| Pentane | 143.1 | 309.2 | 253–393 |
| Freon 113 | 236.5 | 320.8 | 263–373 |
| Acetone | 180.0 | 329.4 | 273–393 |
| Methanol | 175.1 | 337.8 | 283–403 |
| Flutec PP2 | 223.1 | 349.1 | 283–433 |
| Ethanol | 158.7 | 351.5 | 273–403 |
| Heptane | 182.5 | 371.5 | 273–423 |
| Water | 273.1 | 373.1 | 303–473 |
| Toluene | 178.1 | 383.7 | 323–473 |
| Flutec PP9 | 203.1 | 433.1 | 273–498 |
| Naphthalene | 353.4 | 490 | 408–478 |
| Dowtherm | 285.1 | 527 | 423–668 |
| Mercury | 234.2 | 630.1 | 523–923 |
| Sulphur | 385.9 | 717.8 | 530–947 |
| Cesium | 301.6 | 943.0 | 723–1173 |
| Rubidium | 312.7 | 959.2 | 800–1275 |
| Potassium | 336.4 | 1032 | 773–1273 |
| Sodium | 371 | 1151 | 873–1473 |
| Lithium | 453.7 | 1615 | 1273–2073 |
| Calcium | 1112 | 1762 | 1400–2100 |
| Lead | 600.6 | 2013 | 1670–2200 |
| Indium | 429.7 | 2353 | 2000–3000 |
| silver | 1234 | 2485 | 2073–2573 |

## (iii) Types of wick structure:

The wick material is the heart of heat pipe. It generates the capillary pressure and distributes the working fluid to the evaporator section. For proper transport of the fluid back to evaporator against gravity, proper structure of wick is required.

For proper performance of heat pipe, some parameters are to be considered for wick structure.

### 1. Minimum capillary radius

Capillary radius should be small when high heat transfer is required. Specially at the phase change junction at evaporator and condenser. Permeability is a measure of the wick resistance to axial liquid flow. This parameter should be large in order to have a small liquid pressure drop, and therefore, higher heat transport capability.

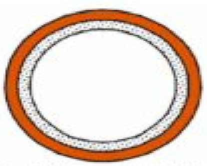
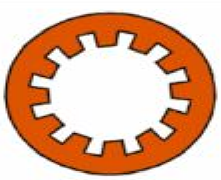
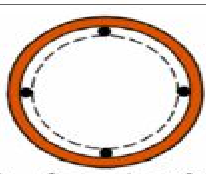
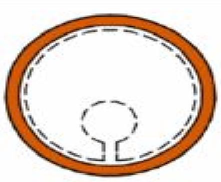
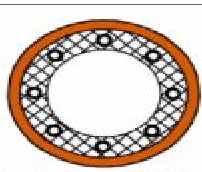
### 2. Effective thermal conductivity

Higher thermal conductivity leads to small temperature drop across the wick structure which is favourable for heat pipe. All the conditions like high permeability, thermal conductivity and small capillary radius are somewhat contradictory terms. So to overcome this condition, optimal design should be considered.

## Types of wick structure:

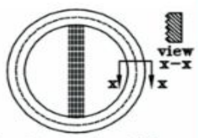
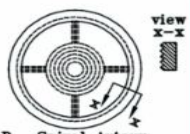
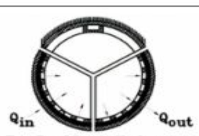
### 1.Homogeneous Wick Structure.

Homogeneous wicks are constructed with one type of material or machining technique. The screen wick is seemingly the simplest and most common type of wick structure. The capillary pressure generated by a screen wick is determined by the size of the rectangular pores between the individual threads. The permeability is determined by the number of wraps and the looseness of the wraps, which creates an annular gaps through which the condensate can flow.

| Wick type | Capillary Pumping | Thermal Conductivity | Permeability | Comments |
|---|---|---|---|---|
|  A. Wrapped Screen | High | High | Low-average | Single or multiple wraps of wire screen mesh. |
|  B. Sintered Metal | High | Average | Low-average | Packed spherical particles, felt metal fibers or powder. |
|  C. Axial Grooves | Low | High | Average-High | Rectangular, circular, triangular, or trapezoidal grooves. |
|  D. Open Annulus | Low | Low | High | Wire screen mesh spaced from wall. |
|  E. Open Artery | Low | High | High | Wire screen mesh formed into artery and wall lining |
|  F. Integral Artery | High | High | Average-high | Homogeneous material with built-in arteries |

## 2. Composite wick structure

Composite wick have small pores for high capillary pressure and large pores for increasing permeability for liquid return path. Here also the simplest type is screen wick which has two sections having different pore sizes.

| Wick type | Capillary Pumping | Thermal Conductivity | Permeability | Comments |
|---|---|---|---|---|
|  A. Composite Screen | High | Low-average | Average | Two or more layers of homogeneous material. The material next to wall has largest pore size. |
|  B. Screen Covered Grooves | High | High | Average-high | Axial grooves covered with one screen. |
|  C. Composite Slab | High | High | High | Slab of homogeneous or non-homogeneous material with circumferential grooves. |
|  D. Spiral Artery | High | High | Average-high | Spiral wire screen mesh and circumferential grooves. |
|  E. Monogroove | Average | High | High | Slab of non-homogeneous material with circumferential grooves. |
|  F. Double-walled artery | High | High | Average-high | Concentric perforated externally grooved inner tube wall. Inner-annuli screen mesh wick. |

## (iv) Power input at evaporator section

Basically power input at evaporator means amount of heat load given. If the amount of heat power is given too much then it will create problems. Due to high power the vapour will achieve high speed and once it achieves speed equivalent to the speed of sound then temperature gradient will be affected too much which eventually results in poor performance. Thus, power and evaporator temperature are related to each other.

## (v) Orientation of heat pipe

Orientation deals with how the heat pipe is placed in the system. This directly affects the capillary action and other parameters. If the pipe is placed in vertical axis, then the condenser should be placed above the evaporator section because the capillary force and gravitational force are aligned in the same direction. This results swift movement of working fluid from condenser to evaporator section.

However proper capillary pumping can overcome gravity action and orientation can be neglected in such cases. This property mainly relies on the wick structure.

## (vi) Use of Nanoparticles with working fluids

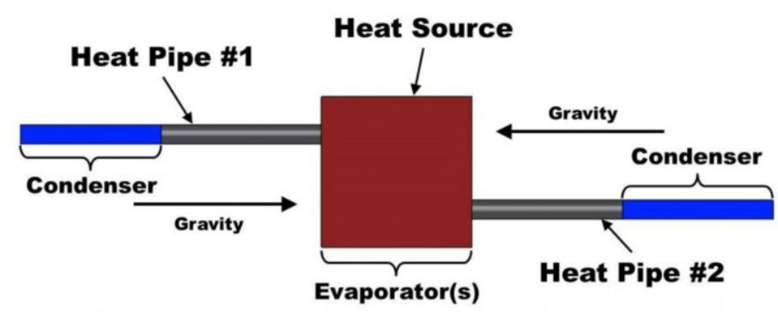
Thermal performance of heat pipe can be improved by blending suitable nanoparticles with working fluids. Addition of alumina can in water results decrease in thermal resistance upto **0.14ºC/w**. Nanofluids used with water are $TiO_2$, $Al_2O_3$, Al etc.

# Operational parameters:

Operational parameters come into picture in working mechanism of heat pipe. These are important parameters which drastically effect heat pipe performance. In order to ensure proper functionality some operational limits are:

## 1. Capillary action

During operation, capillary forces in the wick must overcome the sum of liquid and vapor pressure drops as well as the adverse gravity head and acceleration. Water heat pipes will stop operating under high adverse acceleration, when the wick can no longer return condensate to the evaporator. Due to this condition heat pipe eventually dries out.



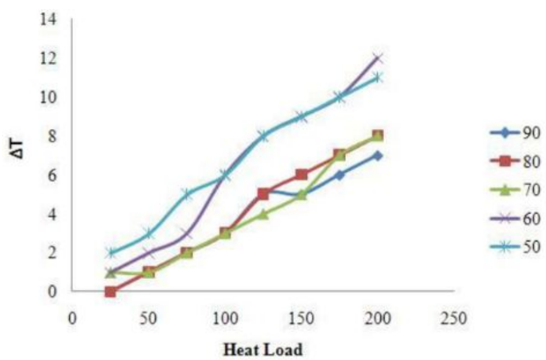

Here, the heat pipe arrangement is two piped such that one pipe is always gravity aided. This arrangement can be done only when the axis and the direction of net gravitational acceleration is known.

Capillary action should always be considered while designing wick structure and the diameters of pores should be provided appropriately.

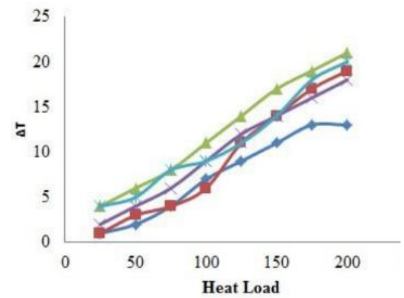
## 2. Filling Ratio

Filling ratio is defined as the percentage of evaporator section volume that is filled by the working fluids. Generally Filling Ratio is considered about 10-70%. Filling ratio higher than 70% causes decrease in thermal performance due to formation of large bubbles in evaporator section. This phenomenon is termed as cavitation.

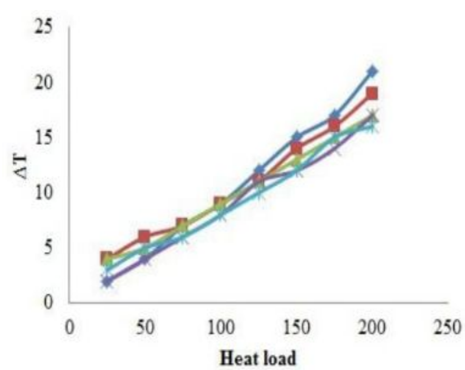
Effects of filling ratio on performance of heat pipe



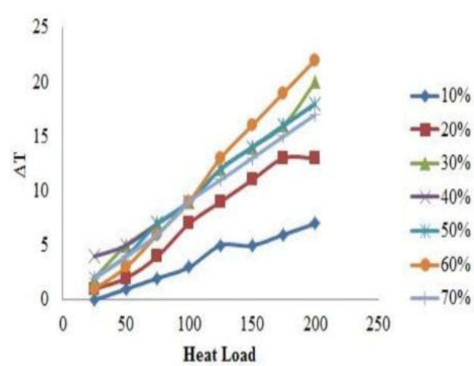

ΔT vs Heat load at 10% filling ratio




ΔT vs Heat load at 20% filling ratio




ΔT vs Heat load at 50% filling ratio




ΔT vs Heat load at 70% filling ratio

## 3. Surface Tension

Surface tension is the tendency of fluid surfaces to shrink into the minimum surface area possible.

Surface Tension **T = F/L**

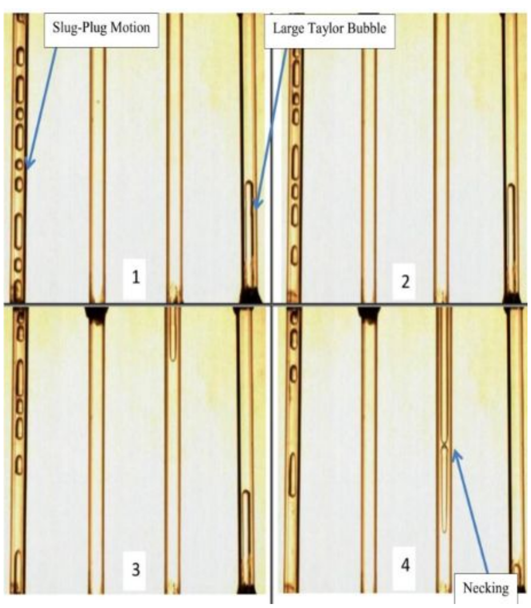
Where F is the force which causes the liquid to behave like an elastic sheet and L is the length in which the force takes place.

Effect of Surface Tension in heat pipe:

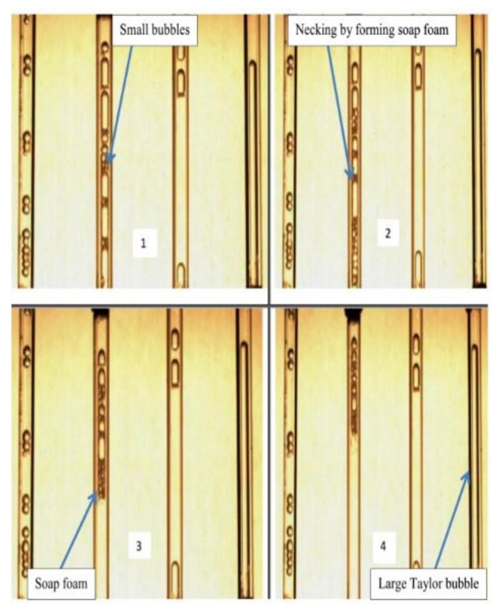
To determine the effect of surface tension, Sodium dodecyl sulfate (SDS) with a chemical formula CH3(CH2)11OSO3Na, has been used to vary the surface tension of distilled water. Three concentrations 500 ppm, 1000 ppm and 5000 ppm have been taken.

## Effect of ST on internal Hydrodynamics

A large number of bubbles (foam) have been formed due to lower surface tension and lower pressure. The foams disappear slowly and form large bubbles. These foams again visible at higher heat input due to fast movement of working fluid. Such foam has not appeared in distilled water.



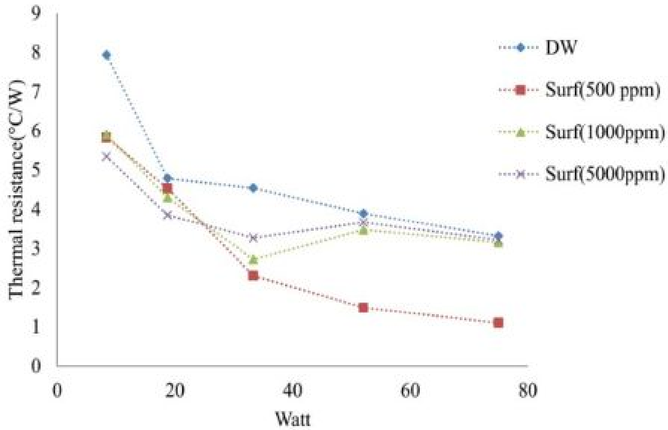

Bubbles at 40%FR distilled water




Bubbles at 40%FR of surfactant

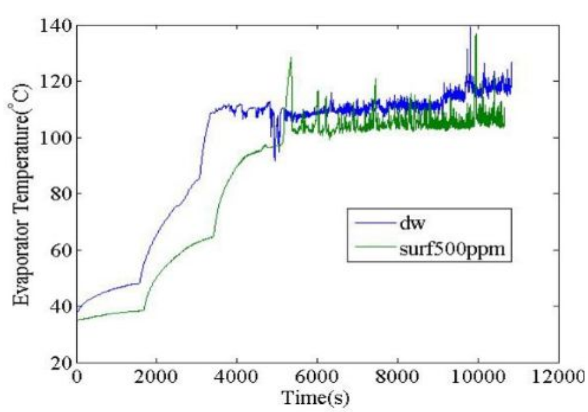
## Effect of Surface Tension in thermal resistance

At 20% FR the thermal resistance with surfactant solution found considerably less as compared to distilled water.. This effect can be due to the fast movement of the working fluid as well as high rate of evaporation due to lower surface tension as it lowers the latent heat of vaporization.




## Effect of surface tension on fluid temperature

The temperature fluctuation is due to pulsating motion of the working fluid. It can be concluded that the evaporator temperature with surfactant solution is always lesser than distilled water due to lower surface tension.



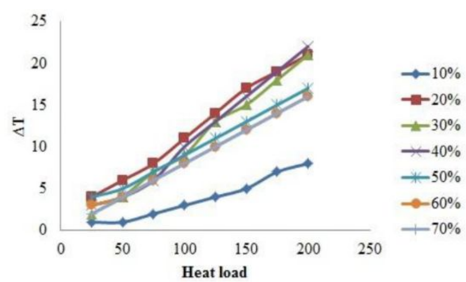

The surfactant solution has shown the significant effect on the thermal performance in all cases as it decreases the surface tension and also helps in early startup of the heat pipe. Hence, it is concluded that surfactant/surface tension improved the thermal performance.

## 4. Inclination angle

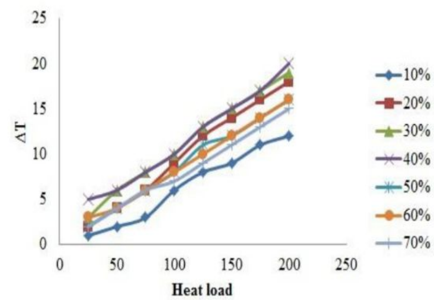
Inclination angle of heat pipe is also an important parameter for efficient functionality. When evaporator receives heat, the working fluid evaporates and reaches to condenser. After condensation, the fluid returns by capillary action.

If the pipe is kept vertical (90$^o$) then the working fluid easily reached due to gravity which shortens the time required.

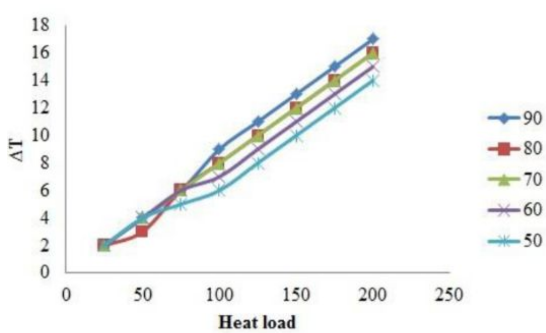
Inclination angle has a characteristic relation with Filling Ratio. Usually these parameters are considered simultaneously



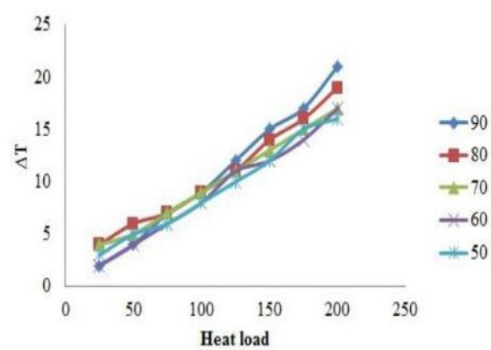

$\Delta$T vs heat load at $70^0$ inclination angle




$\Delta$T vs heat load at $60^0$ inclination angle




$\Delta$T vs heat load at $90^0$ inclination angle




$\Delta$T vs heat load at 30% FR and $70^0$

## 5. Data reduction value :

Effectiveness of the heat pipe can be represented by a system of thermal resistance.

$$R = T_e - T_c / Q \quad 0C/W$$

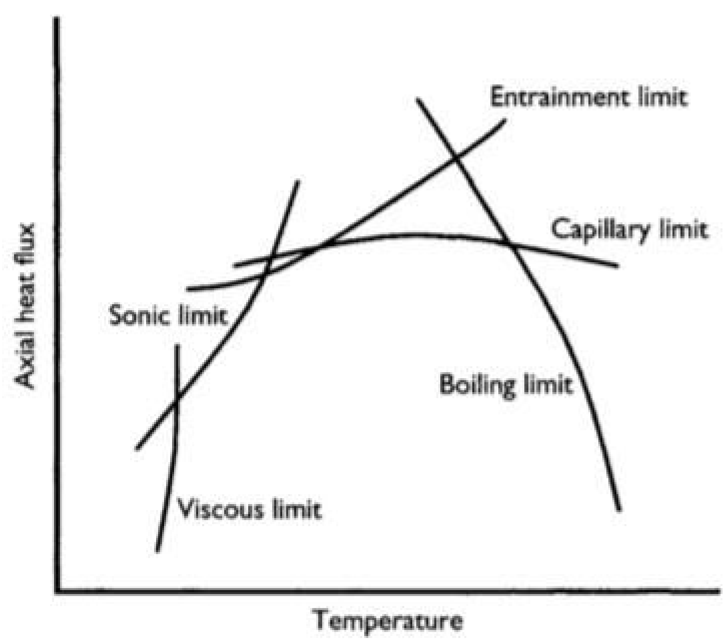
Overall heat transfer co -efficient h of the heat pipe can be given by

$$h = Q / A(T_e - T_c) \quad W/m2.0C$$

Here, Tc is average value at condenser temp.
Te is the average value at evaporator.
Q is the input heat.
A is the heat transfer surface area, at the evaporator.

## 6. Operational limits

Some operational limits are to be considered in order to ensure efficient thermal performance. Individual effects of these parameters are shown in the following **Axial heat flux vs Temperature graph**



## (1) Sonic limit

Due to high power input at the evaporator, the vapor generated sometimes achieve the speed of sound (sonic value). Due to this, compressibility effects which changes overall pressure. So the maximum vapor speed should be less than the sonic limit. The sonic limitations has to be considered at the minimum temperature, 30$^{o}$C.

## (2) Viscous limit

At low temperatures, the vapor pressure difference between the evaporator and condenser becomes very small. Viscous forces are dominant in this condition and limits the operation of heat pipe. This kind of situation generally occur at startup. After prolonged operation this effect is neglected due to increase in room temperature.

## (3) Entrainment limit

The liquid and vapor flows in different directions in the heat pipe. When the vapor reaches the condenser it is going to affect the liquid in the inside of the wick. If the shear force of the vapor is big compared to the surface tension in the liquid there is likelihood of entrainment of liquid drops in the condenser.

The Weber number is the ratio between inertial vapor forces and liquid surface tension forces and is defined as,

$$We = \frac{\rho v^2 z}{\sigma}$$

where index v relate to vapor velocity, σ is the surface tension and z are the dimensions characterizing the vapor liquid surface.

Thus Entrainment is calculated as

$$Vc = \frac{(2\pi\sigma l)^{1/2}}{(\rho v^2)^{1/2}}$$

### (4) Capillary limit

$$\Delta P_c \leq \Delta P_l + \Delta P_v + \Delta P_g$$

where indexes c,l,v,g refers to capillary, liquid, vapor and gravity. If this condition is not met, the wick will dry out in the evaporator region and the heat pipe will not operate. An expression for the maximum flow rate may be obtained if it is assumed that

- the liquid properties do not vary along the pipe
- the wick is uniform along the pipe
- the pressure drop due to vapor flow can be neglected

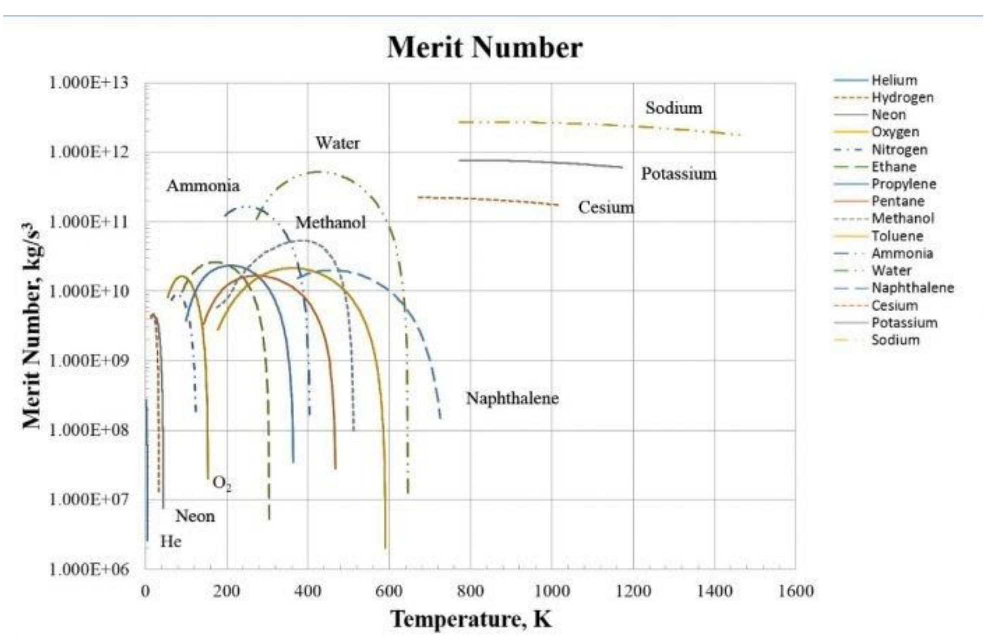
## Merit Number:

It depends only on the properties of the working fluid and is called Merit number.

$$M = \frac{\rho \sigma L}{\mu}$$

Merit number gives a relation between material used in outer shell and working fluid. Suppose we select a specific working fluid, then that metal should be selected as outer shell which has the highest merit number.

If we select water as working fluid, then copper must be used as shell material as it has the highest merit number with respect to water.



### (5) Boiling limit

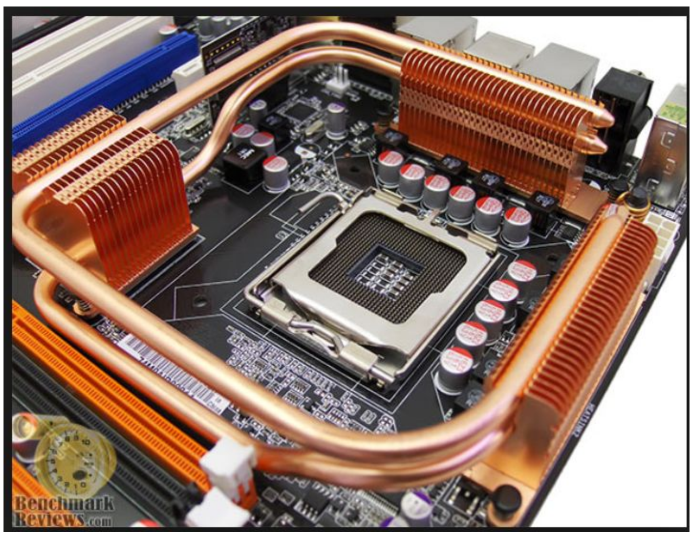
At high temperature and heat flux there is going to be nucleate boiling in the wick of the evaporator. Vapor may then block the liquid to be supplied to all parts of the evaporator. It is desirable to reduce the chance of nucleation. A working fluid degree of superheat to cause nucleation is given by

$$\Delta T = \frac{3.06\sigma l T sat}{\rho v L \delta}$$

where δ is the thermal layer thickness and is taken as a representative value of 25μm to compare working fluids. It is desirable to have a working fluid with high value of superheat, $\Delta T$.

# Applications of heat pipe:

1. **Electronic Devices**

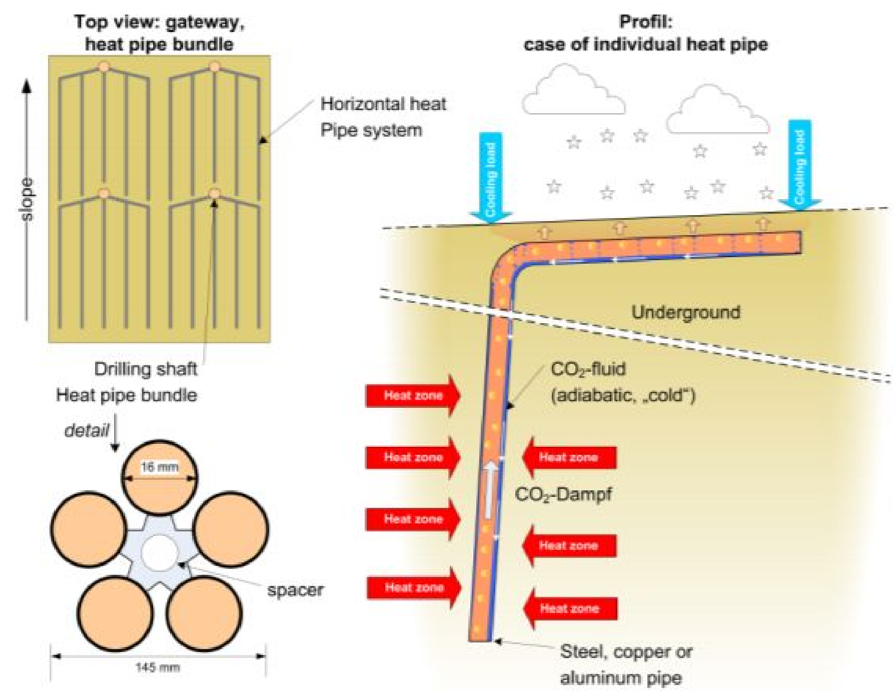



One of the largest applications of heat pipe technology is the cooling of electronic components such as central processing units (CPUs), circuit boards, and transistors. CPU’s have high performance capacities for processing this leads to higher heat density, resulting in increasing CPU temperature, threatening a shortened life of the chip or resulting in malfunction or failure. A conventional method used to keep a CPU from overheating is to use an extruded aluminum heat sink.

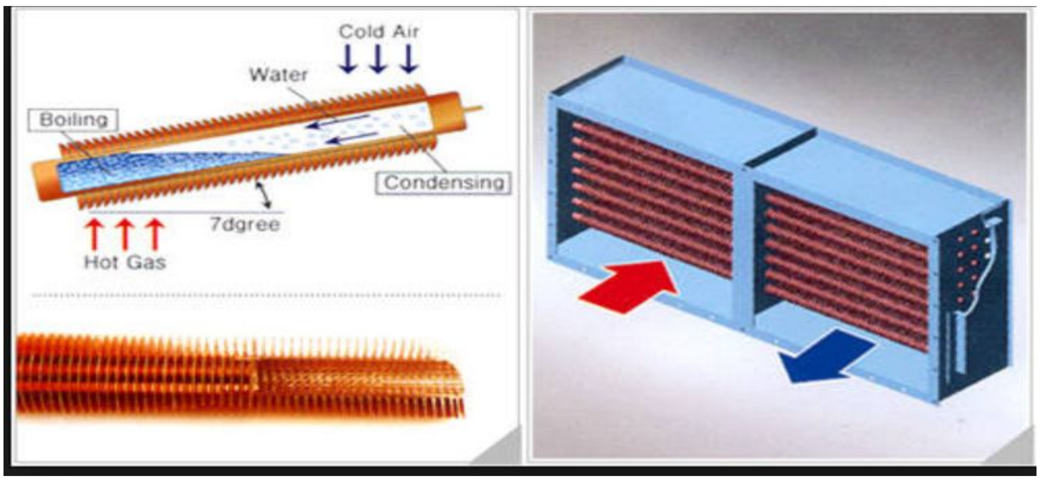
## 2. De-icing:

In very cold country where snowing conditions exist, frequent snowfall can cause a thin layer of ice on roads. This is a very risky condition and cause skidding of vehicles.

To compensate this condition, a heat pipe arrangement is made where evaporator is fixed underground 2-3 metres and condensator outlet is placed on the road. This arrangement melts the ice due to output heat and it ensures proper friction.



### 3. Air Preheater

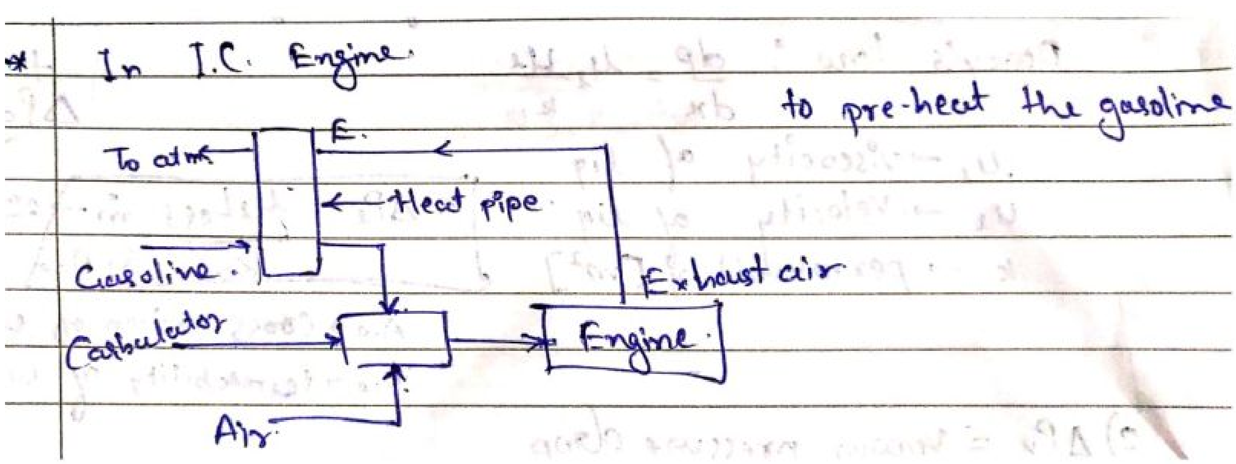



Hot waste flue gases coming from boiler chimneys are hazardous to the environment if they are directly discharged in the atmosphere. The heat from these gases can be extracted using a heat pipe to preheat the air used to warm the feed water.

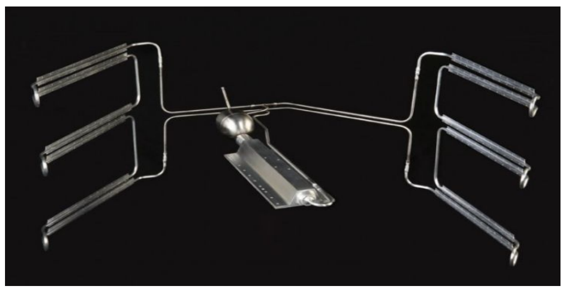
$$\% \text{ of heat recovery} = maCpa(Ta_2 - Ta_1) / mgCpg(Tg_2 - Tg_1)$$

## 4. I.C Engines

Fuels entering the chambers can be preheated using heat pipes. Due to preheated fuel, combustion process becomes feasible and efficiency of engines can be increased. Heat pipe use the heat of exhaust gases and transfers it to the fuel before entering the carburetor.



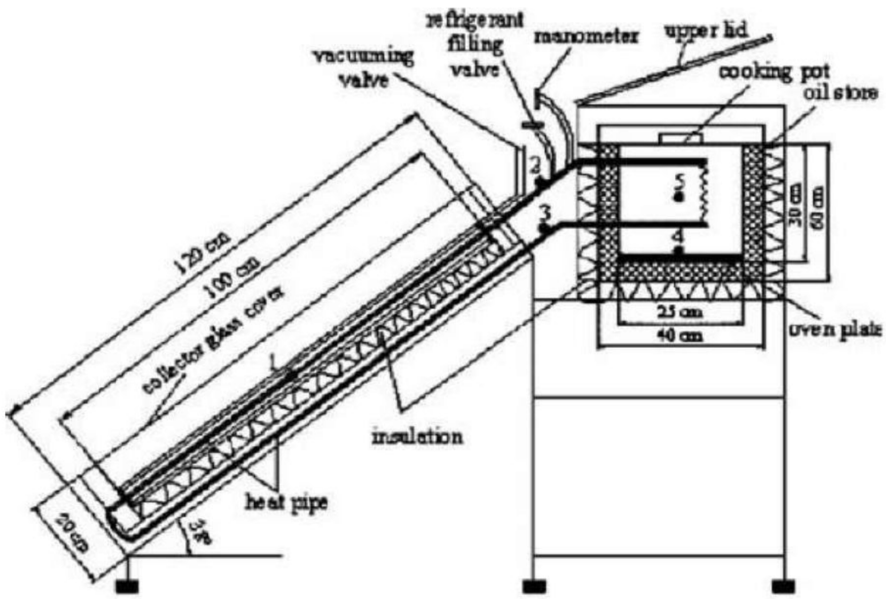
## 5. Aerospace Technology



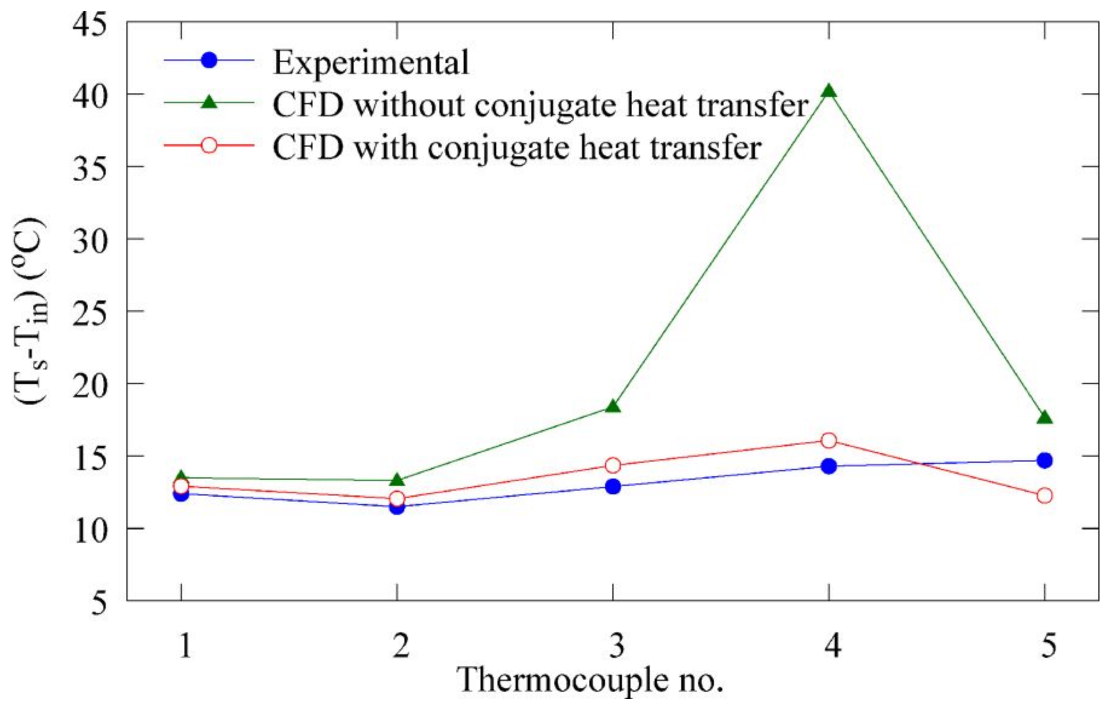
Heat pipes have wide application in the area of spacecraft cooling and temperature stabilization. While in orbit, an observatory may be fixed on a single point such as a star. Consequently, one side of the capsule will be subjected to intense solar radiation while the other is not. Heat pipes in this situation are used to transport heat from the side facing the sun to the cold side away from it, thus equalizing the temperature of the structure.. To achieve this, heat pipes are commonly used to affect heat transfer and heat redistribution functions in the microsatellites.

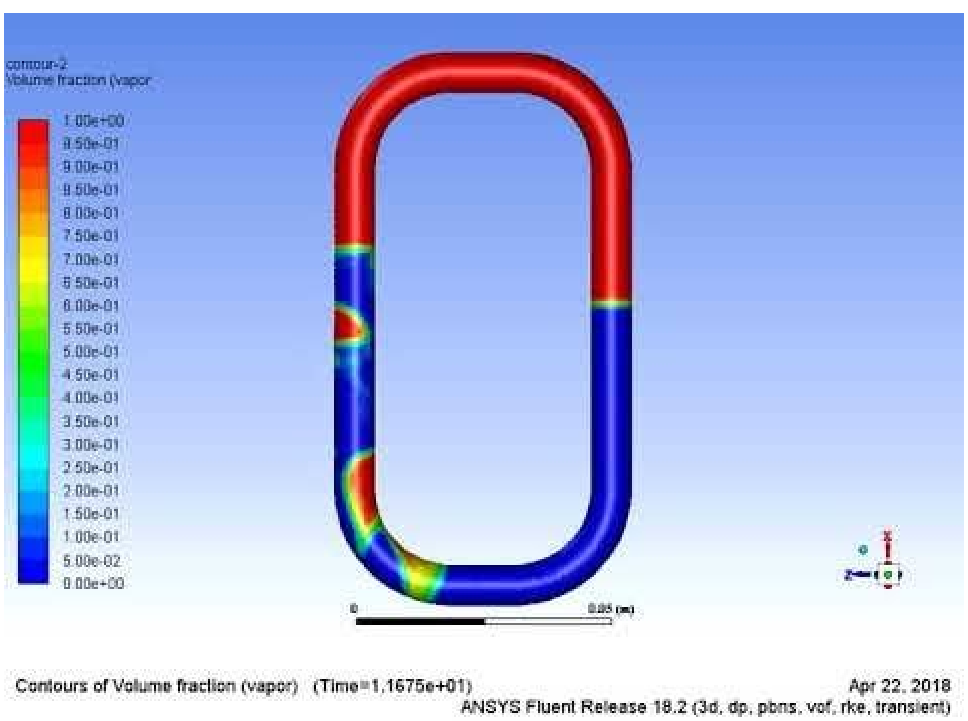
## 6. Solar Cooking

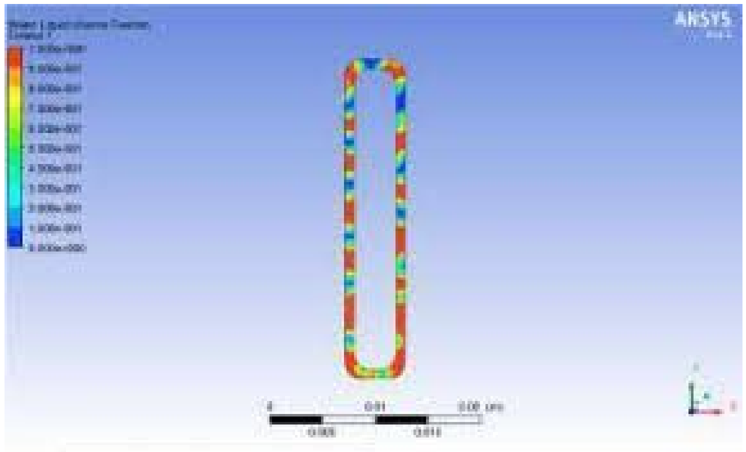
Preparation of food requires some amount of energy which generally comes from wood, nowadays the rate of wood fuel consumption exceeds its replacement, and this results in deforestation, pollution, soil erosion and global warming. Although electric cooking is efficient, use of fossil fuels emit gases like CO2 & SO2. The use of solar cooker technology is an alternative solution to the fuel problem. Heat pipes are utilized for solar cookers in transporting heat from the heat source to its destination.



# Results and conclusion






So we have seen how different parameters influence the thermal performance of heat pipe. By changing different properties, different outputs can be generated.