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DESIGN OF HEAT PIPE AND ANALYSIS OF HEAT TRANSFER LIMITS FOR DIFFERENT WORKING FLUIDS

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Abstract

Thisexisting study emphases on the design of heat pipe and verification of excel mathematical model for calculating analysis of heat transfer limits of heat pipe for different working fluids.The calculations of the various variations of the wick structure properties and working fluid of heat pipe are existing in graphs as a dependence of the heat transport limitations on the operational temperature. The entrainment limitation, capillary limitation and boiling limitation are plays important role in heat pipe performance.Usually, the heat pipe parameters like,wick structure parameters and the thermophysical properties of the working fluideffects on the limitation values of heat pipe.The thermophysical properties of each working fluid are stable, At the temperature ranges, the thermophysical properties of each working fluid are stable and they can't change.The present study focuses on the analysis of effect of heat transfer limits on the cooling power of the heat pipe. This mathematical model can be used to carry out further studies on heat pipe like, different combinations of working fluids and wick structures to optimize the design of heat pipe for various applications

Keywords: *Heat Pipe, Thermal Analysis, Heat Transport Limits, Thermal Resistance,Vapor–liquid interface.*

1. Introduction

The heat pipe is a device, that transfers heat from a hot reservoir to a cold reservoir by using vapor–liquid phase-change phenomenon and capillary forces generated by a wick or porous material and a working fluid.The heat pipe is composed of a container lined with a wick that is filled with liquid near its saturation temperature. The vapor–liquid interface, generallyoriginate near, the inner edge of the wick, separates the liquid in the wick from an open vapor core. Heat available into the evaporator is obtained from passed through the container to the liquid-filled wicking material, that converts the liquid to evaporate and vapor to flow into the open core region of the evaporator. The capillary forces, generated by the evaporating interface increase, the pressure difference between the vapor and liquid. The vapor in the open core flows, out of the evaporator through the adiabatic region and into the condenser.

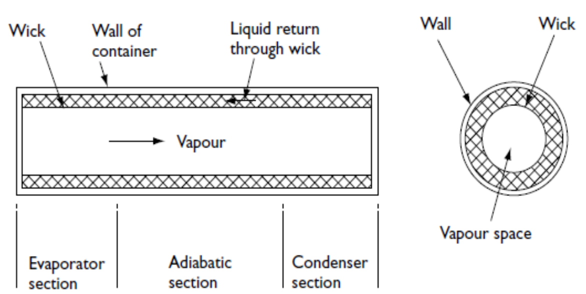


Fig 1: The Main regions of the heat pipe. [10]

The cylindrical geometry of the heat pipe is shown in Fig.1.The components of heat pipe are a sealed container (pipe wall and end caps), a wick structure, and a small amount of working fluid which is equilibrium with its own vapor. The length of the heat pipe is divided in to three parts: evaporator section, adiabatic (transport) section and condenser sectionThe electronics cooling, spacecraft applications and other several applications of heat transfer arewidely used heat pipes. Although they can transfer huge rate of heat in a short range, they have operating limits, the heat transfer capacity of the heat pipe is evaluated by using the capillary limit, the viscous limit, the entrainment limit, the sonic limit and the boiling limit. These limits under which heat pipe works safely. [1]

The parameters that affect the limits are the properties of the working fluid, the structure of the wick, the orientation of the pipe and the length and the diameter of the pipe etc. It is necessary to know these effects on the performance. [3]

1.1. Operating Principle

Working principle of the heat pipe is simple. As heat is accumulated into the heat pipe, the working fluid in the wick structure evaporates. Due to evaporation, a pressure difference occurs between two ends of the pipe. The working fluid is driven by this pressure gradient and it flows through the vapor space to the other end of the pipe, which is the condenser. At the condenser end, heat is removed from the heat pipe, causing the working fluid to condense. The condensed liquid goes into the wick structure. Capillary forces cause the liquid to flow back to evaporator and the cycle is completed. There is no activating equipment like a pump in the system. It is simple and consists of only a closed pipe, a wick structure and a working fluid. Therefore, it is called passive. Since the coolant exists in two-phase at the same time, it is called two-phase device. [8]

2.Therotical Analysis

2.1 Operating Limits [10]

The heat transfer limitation can be any of the above limitations depending on the size and shape of the pipe, working fluid, wick structure, and operating temperature.The heat transfer limit depends on operating temperature, thermophysical properties of working fluid and the wick structure. The heat transfer limits of heat pipe are:

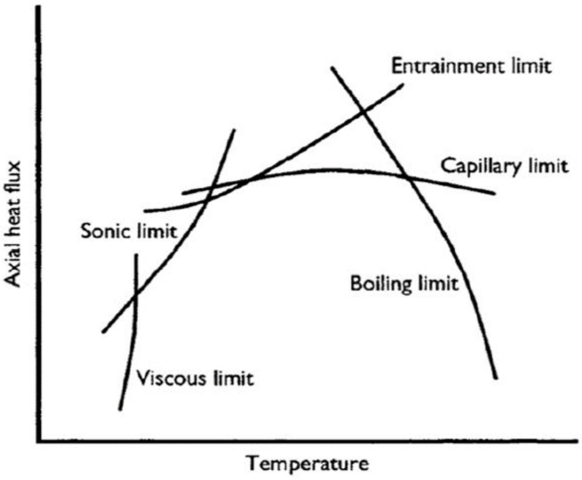


Fig.2 Heat transfer limitation [10]

Capillary Limit- The capillary limit is the most commonlyencountered limitation in the operation of low-temperature heat pipes. It occurs when the pumping rate is not sufficient to provide enoughliquid to the evaporator section. This is due to the fact that the sum ofthe liquid and vapor pressure drops exceeds the maximum capillarypressure that the wick can sustain.

$$\Delta \mathrm{P_c} = \Delta P_l + \Delta P_g + \Delta P_v$$

$$r_c = \frac{w + d_w}{2}$$

$$\Delta \mathrm{P_c} = \frac{2\sigma \cos \theta}{\mathrm{r_c}}$$

$$\varepsilon = 1 - \frac{1.05 \times \pi \times N \times D}{4}$$

$$K = \frac{d_w^2 \times (1-\varepsilon)^3}{66.6 \times \varepsilon^2}$$

$$\Delta P_l = \frac{\mu_l \times Q_c \times L_{eff}}{\rho_l \times L \times A_w \times K}$$

$$\Delta P_g = \rho_l \times g \times l_{eff} \times SIN\emptyset$$

$$\Delta P_v = 0.9^{12} \times k_v \times Q$$

Boiling Limit - If the radial heat flux in the evaporator section becomes too high, the liquid in the evaporator wick boils and the wall temperature becomes excessively high. The vapor bubbles that form in the wick prevent the liquid from wetting the pipe wall, which causes hot spots. If this boiling is severe, it dries out the wick in the evaporator, which is defined as the boiling limit. However, under a low or moderate radial heat flux, low intensity stable boiling is possible without causing dry out. The boiling limit is often associated with heat pipes ofnon-metallic working fluids. For liquid-metal heat pipes, the boilinglimit is rarely seen.

$$l_{eff} = L_a + \frac{L_e + L_c}{2}$$

$$k_{eff} = \frac{k_l[(k_A + k_w) - (1-\varepsilon)(k_l - k_w)]}{(k_A + k_w) + (1-\varepsilon)(k_l - k_w)}$$

$$Q_b = \frac{2\pi l_{eff} \times k_{eff} \times T_v}{A_v \times h_{fg} \times \rho_v \times ln(\frac{r_i}{r_v})}\left[\frac{2\sigma}{r_n} - (\Delta \mathrm{P_c})_{max}\right]$$

Entrainment Limit - A shear force exists at the liquid-vapor interface since the vapor and liquid move in opposite directions. At high relative velocities, droplets of liquid can be torn from the wick surface and entrained into the vapor flowing toward the condenser section. If the entrainment becomes too great, the evaporator will dry out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe.

$$Q_e = \pi {r_v}^2 L \sqrt{\frac{2\pi\rho_v\sigma_l}{z}}$$

Sonic Limit-The evaporator and condenser sections of a heat pipe represent a vapor flow channel with mass addition and extraction due to the evaporation and condensation, respectively. The vapor velocity increases along the evaporator and reaches a maximum at the end of the evaporator section. Therefore, one expects that the vapor velocity at that point cannot exceed the local speed of sound. This choked flow condition is called the sonic limitation. The sonic limit usually occurs either during heat pipe startup or during steady state operation when the heat transfer coefficient at the condenser is high. The sonic limit is usually associated with liquid-metal heat pipes due to high vapor velocities and low densities. Unlike the capillary limit, when the sonic limit is exceeded, it does not represent a serious failure.

$$Q_s = \rho_v L \sqrt{\frac{rRT_v}{2(r-1)}}$$

The Merit number - It will be shown, with reference to the capillary limit, that if vapour pressure loss and gravitational head can be neglected then the properties of the working fluidwhich determine the maximum heat transport can be combined to form a figure ofmerit, M.

$$M = \frac{\rho_l \times \sigma \times L}{\mu_l}$$

3. Development of Mathematical Model

Heat pipes are devices that can transfer large amount of heat with small temperature differences between evaporator and condenser parts. This property can be seen better when a heat pipe is compared with aluminum or a copper rod. Heat pipes cannot operate in any condition, without being affected by anything. There are some factors that the performance of the heat pipe depends on. The heat pipe has a limited heat transport capacity, and this capacity is determined by various factors like working fluid properties, wick structure properties, working conditions etc. There are some governing limits like capillary limit, viscous limit, entrainment limit, sonic limit and boiling limit for the maximum heat transport capacity of a heat pipe.

In this study, the governing limits for the heat transfer capacity of the heat pipe are studied by using Excel mathematical model. The heat transfer capacity of a heat pipe depends on the various parameters. [1]

Table1: Parameters affecting the heat pipe performance

Wick Type	Screen Mesh		
Working Fluid	Ethanol	Methanol	Water
Heat pipe material	Copper	Copper	Copper

The mathematical model can be used for following purposes;

1.To see the effects of various parameters on the heat transfer capacity of the heat pipe.

2.To obtain the heat transfer capacity of a heat pipe for specific conditions

3.1 Analysis of the Screen Mesh Wick

First analyses are performed for wire screen meshes, selected as wick structure. Three types of working fluids are used: Water, Ammonia and Ethanol. There are two types of materials used in the analyses. For water and ethanol copper is the compatible material and for the ammonia aluminum is the compatible material. Copper is not used for the ammonia, since it is not compatible. It leads to corrosion and chemical interaction between working fluid and pipe material. Therefore, Water-Copper, Ammonia-Aluminum and Ethanol-Copper combinations are used in the analyses. [1]

The heat pipes used in the analyses have same geometrical parameters. However, working fluid, heat pipe material and wick material are different. Table 2 gives specifications of heat pipe selected for the analysis. For calculating heat transport limitations of heat pipe with screen mesh, the main parameters of the heat pipe such as inner container radius, cross-sectional radius of vapor core, evaporation length of the heat pipe, adiabatic length of the heat pipe and condensation length of the heat pipe are needed. For calculations of main parameters of heat pipe, mentioned above, few other parameters are required to be calculated first.

In the analyses, the temperature range for water is selected from 20^0C to 140^0C. This range of temperature corresponds to melting and boiling points of water. Since the melting point is lower and boiling point is higher, the saturation pressure is equal to atmospheric pressure. At higher temperatures, sealing problems may occur due to pressure difference between inside and outside of the pipe. Moreover, this range is the operating temperature range for most of the electronic equipment's.

Table 2: Heat pipe configuration [2]

The temperature range of the Ethanol is selected as It

Inner Diameter (m)	0.003259
Total Length (m)	0.07
Evaporative Length (m)	0.02
Condenser Length (m)	0.03
Adiabatic Length (m)	0
Working fluid and pipe material	Water for Copper Ethanol for copper Methanol for Copper
Wick structure	Wire Screen mesh
Number of meshes	500
Wire diameter (m)	0.00002159
Number of layers	3

from 30^0C to 130^0C is selected to see the performance of the heat pipe for lower temperatures where water cannot be used, and in order to make a comparison of Ethanol and water in the temperature range
of Water. With temper Methanol temperature range is 30^0C to 130^0C.Using these temperature ranges and the specified heat pipe properties, analyses are performed for three types of working fluids.

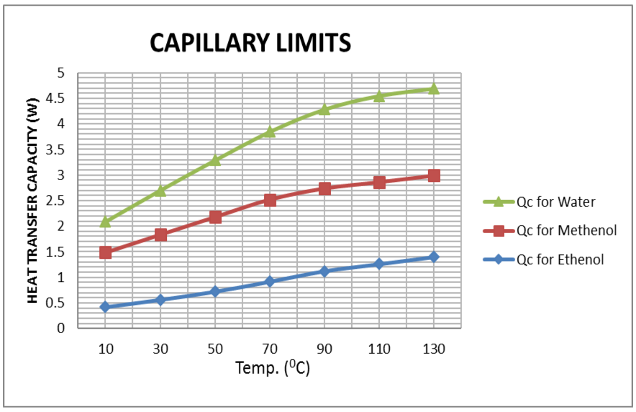


Fig. 3 Result of Calculation for 500 Mesh/inch Wire Screen Wick structure with 3 Layers, effect on capillary limit, for 3 different types working fluid

The Fig 3-5 shows the general behavior of the heat pipe limits. With this above configuration of heat pipe it is seen that the dominant limit that determine the heat transfer capacity of the heat pipe is capillary limit. The heat transfer value for the capillary limit is lower than the other limits.

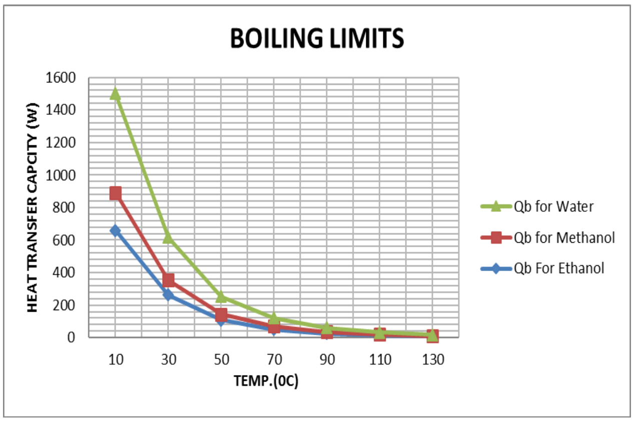


Fig. 4 Result of Calculation for 500 Mesh/inch Wire Screen Wick structure with 3 Layers, effect on boiling limit, for 3 different types working fluid

For the boiling limit, it is seen from the graph that as the temperature increases, the heat transfer capacity of the boiling limit decreases. This is because of the bubble formation theory. The vapor density increases as the temperature increases and surface tension decreases, which affect the pressure difference of liquid-vapor interface, this pressure difference and the temperature is the main factor for the bubble formation. As temperature increase the vapor pressure increase and surface tension decrease, resulting pressure difference decrease. Therefore, decrease in the boiling limit as temperature increase.

It is obvious from the Figure 5 it seen that entrainment limit, as the temperature increases, the liquid viscosity decreases. As a result, viscous forces between liquid and vapor at liquid-vapor interface decrease, causing an increase in the entrainment limit of the heat pipe. If the formula of entrainment limit is investigated, the increase of vapor density results in increase of heat transport capacity for entrainment limitation.

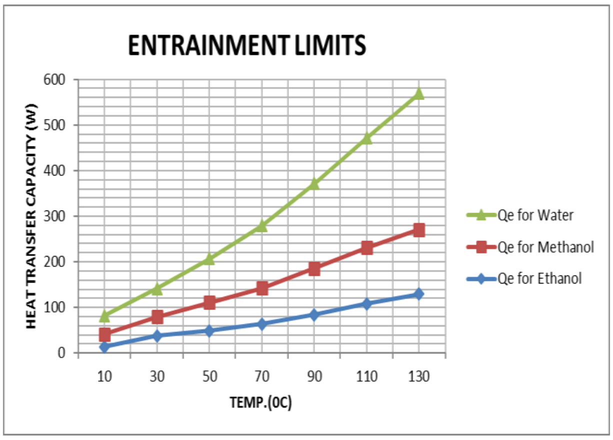


Fig. 5Result of Calculation for 500 Mesh/inch Wire Screen with 3 Layers, effect on entrain. limit, for 3 diff. types working fluid

Table 3: Comparison of the performances for 3 types of working fluid [2]

Wick Properties	3 Layers of 100 mesh/inch wire screen mesh with wire diameter of 0.00002159			
Working Fluid	Water	Methanol	Ethanol	Governing Limit
Max. Capacity (W)	1.70484	1.068357	1.399418	Capillary Limit
Temp.	413	403	403	
Minimum Capacity (W)	0.603481	1.589546	0.417814	Capillary Limit
Temp.	293	283	283	

3.2 Analysis of layers' number effect

Layers number is another parameter that affects the performance of a heat pipe. Increasing or decreasing the layer number may have different effect on the heat transfer capacity of the heat pipe. Analyses are done to see the performance of heat pipe if the layer number of meshes of wick structure is decreased or increased. For this purpose,

Firstly, the layer's number of main configuration is decreased from three to two, keeping the other parameters constant. Secondly, to the see the effect of layers' number increase on the heat transfer limits, the layer's number of the main configuration increased from three to five by keeping all other parameters constant. The effects on the operating limits are as follows.

a) Capillary Limit

It is obvious from the Figure 6 that there is a decrease in heat transfer values of capillary limit, when the layer of wick structure is decreased from three layers to two layers. Decrease in the number of layers means decrease in wick area and increase in vapor space. If the vapor space increases, more vapors can flow from evaporator to condenser.

However, this increase in flow increases the liquid flow losses inside the wick structure, causing a decrease in the total heat transfer capacity of the heat pipe, in terms of capillary limit. This causes decrease of capillary limit values. On the other hand, the increase in layer number causes increase in capillary limit.

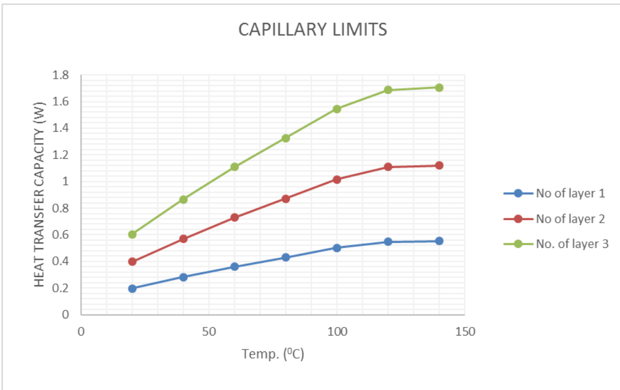


Fig.6 Effect of the Layers No. on Capillary Limit for Water

b) Entrainment Limit

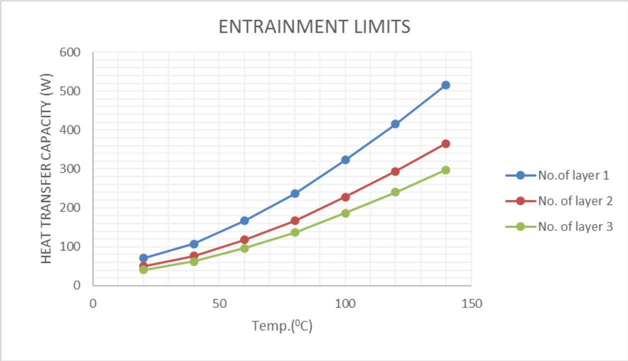


Fig.7 Effect of the Layers No. on Entrainment Limit for Water

As can be seen from the Fig. 7, decreasing the layer number of wick structure causes increase in the heat transfer capacity for entrainment limit. Decreases the layer number means increase the vapor space area which affects the entrainment limit. Effect of shear forces between liquid and vapor becomes less and as a result, more vapors can be transferred from evaporator to liquid.

Layers number increases causes in opposing effect when it is compared with the effect of layer's number decrease on entrainment limit. Heat transfer capacity of the entrainment limit decreased with increase in layer number. The reason is if the layer's number increases, vapor flow area decreases causing an increase in shear forces losses. This decreases the capacity of the heat pipe in terms of entrainment limit.

c) Boiling Limits:

The Fig.8 shows the effect of decrease in layer number to heat transfer capacity of heat pipe regarding sonic, boiling and viscous Limit

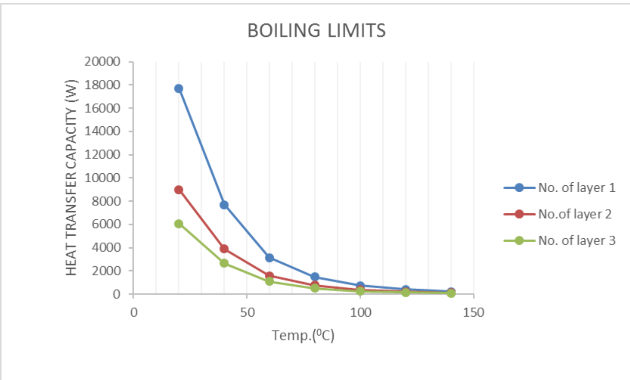


Fig.8 Effect of Layer No. on Boiling Limit for Water

Examining the Fig.6, it is seen that the situation is different than capillary limit. Decrease in layer number causes a decrease in capillary limit. However, for viscous, sonic and boiling limits, decrease in layer number provides increase in heat transfer capacity.

The layer number change affects the boiling limit since it changes the vapor area and as a result the vapor diameter. The boiling limit also changes because of vapor diameter changes. For boiling limit, it is obvious from the graph that layer number decrease affects the heat transfer capacity of boiling limit at lower temperatures. The decrease in layer number causes increase in boiling limit. At higher temperatures, the results of both cases are closer. Similarly, the layer number increase affects the boiling limit at lower temperatures. The heat transfer capacity of boiling limit decreases with increase in layer number. However, at higher temperatures, it seems that layer number increase does not affect the boiling limit so much.

3.3 Analysis of mesh number effect for wire screen meshes

One of the important parameters that have a dominant effect on heat pipe performance is the number of meshes used in wick structure. The wick structure provides capillary pressure difference which is the driving force for the liquid-vapor flow between evaporator and condenser sections.

As the number of mesh decreases, the distance between wires (w) and the diameter (d) increases. As result of increase in distance, the frictional losses in liquid phase and capillary pumping pressure decreases.

The result analysis performed with 500,250,180 mesh/inch wire screen mesh can be seen in below figures 6-8. The analyses are performed for water as working fluid, keeping the specified heat pipe properties constant, except mesh number.

a) Capillary Limit:

It is obvious from the Figure 9 it seen that the heat transfer values for the all limits except capillary limit are decreased for water, when compared with the Water heat pipe 500 mesh/inch with other Copper screen mesh. As result the temperature increased the capillary limit increase. All the other operating limits are not changed same as water heat pipe with 500 mesh/inch screen mesh. Therefore, the governing limit is capillary limit. After 285K capillary limit becomes determine for the heat transfer capacity of the heat pipe.

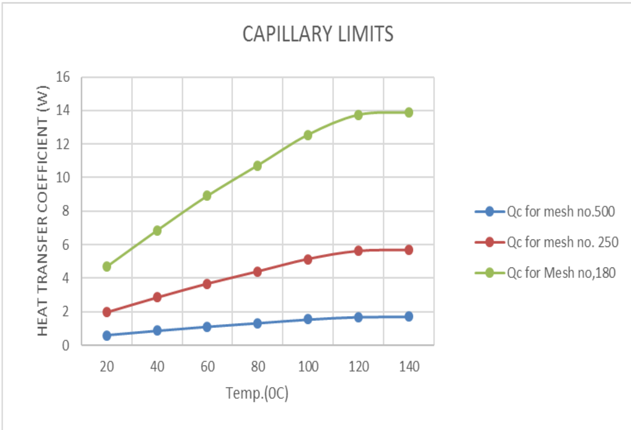


Fig. 9 Effect of the screen mesh No. on capillary Limit for Water

c) Entrainment Limit

As can be seen from the Fig.10, decreasing the screen mesh number of wick structure causes increase in the heat transfer capacity for entrainment limit.Decreases screen mesh number means increase the vapor space area which affects the entrainment limit. when compared with the Water heat pipe with 500 mesh/inch with other Copper screen mesh number.

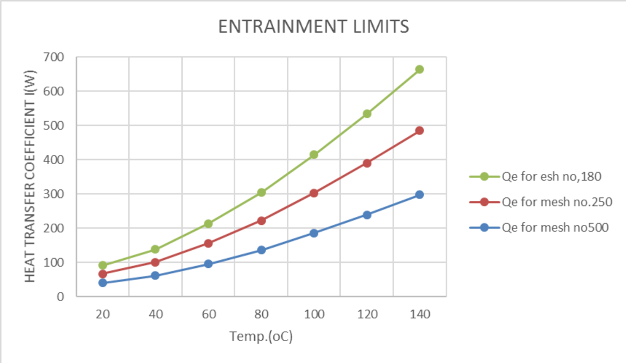


Fig.10 Effect of the screen mesh No. on Entrain. Limit for Water

c) Boiling Limit:

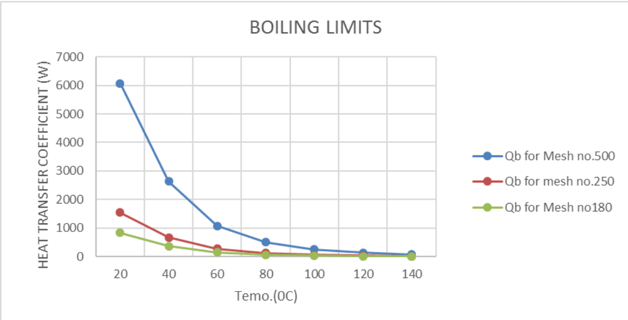


Fig. 11 Effect of the screen mesh No. on Boiling Limit for Water

The screen mesh number change affects the boiling limit since it changes the vapor area and as a result the vapor diameter. The boiling limit also changes because of vapor diameter changes. For boiling limit, it is obvious from the graph that screen mesh number decrease affects the heat transfer capacity of boiling limit at lower temperatures. The decrease in screen mesh number causes decrease in boiling limit. At higher temperatures, the results of both cases are closer. Similarly, the layer number increase affects the boiling limit at lower temperatures. The heat transfer capacity of boiling limit decreases with decrease in screen mesh number. However, at higher temperatures, it seems that screen mesh number increase does not affect the boiling limit so much.

Design of Heat Pipe

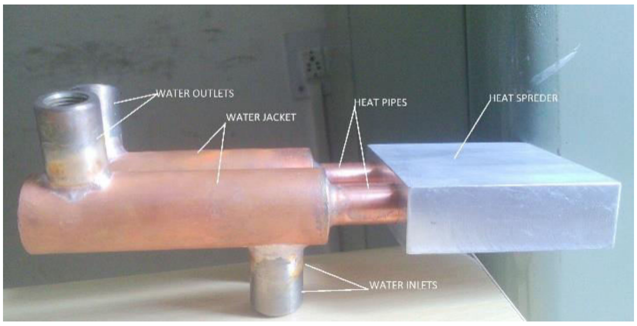
With the help of above excel mathematical model,thedesign of heat pipe using as a heat sink of thermoelectric generator which is used to remove waste heat from IC engine exhaust is constructed. The configuration for the designed heat pipe given in table no.4

The heat pipe shown in the Fig.12 is used as a heat sink at hot side of thermoelectric generator is used to remove waste heat from IC engine exhaust

Table 4: Heat pipe configuration

Diameter (m)	0.01
Total Length (m)	0.13
Evaporative Length (m)	0.04
Condenser Length (m)	0.07
Adiabatic Length (m)	0.02
Working fluid and pipe material	Water for Copper
Wick structure	Wire Screen mesh
Number of meshes	60
Wire diameter (m)	0.000017
Number of layers	2

a) Details of heat pipe and spreder



b) Assembly of heat pipe and spreder

Fig.12 Heat pipe with heat spreder

The assembly of heat pipe with heat spreder shown in fig Fig.12(b). The sprederhaving dimensions of 50*50*16 mm and two bore size 10mm each in which heat pipe fitted. This assembly placed on cold side of thermoelectric generator and water is passed through the outer water jacket at the condenser section. In this process the heat pipe works as a heat sink at the cold side of thermoelectric generator and remove heat from cold side of TEG.

Conclusions

The entrainment limitation, capillary limitation and boiling limitation are plays important role in heat pipe performance. Usually, the heat pipe parameters like, wick structure parameters and the thermophysical properties of the working fluid effects on the limitation values of heat pipe. Obtained Graphic dependences curve expressly can be used to understand the small changes in theheat transport limitation of heat pipe.

Generally, the capillary limit is the primary maximum heat transport limitation of heat pipe. Water provides the maximum heat transfer capacity for the temperature range of 293 K – 413 K. Therefore, water is better than methanol and ethanol for room temperature applications. The first analyses are done using water as working fluid. In these analyses, the effects of different properties of wire screen mesh is to be investigated. The heat transfer capacity for three layers of 500 meshes/inch wick structure provides better than other working fluid

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