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Operating limits of heat pipe heat exchanger for air conditioning Application

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ABSTRACT

Heat pipe heat exchanger (HPHX) is an excellent device used for heat recovery in air conditioning systems. Among the many outstanding advantages of using the heat pipe as a heat transmission device are constructional simplicity, exceptional flexibility, accessibility to control and ability to transport heat at high rate over considerable distance with extremely small temperature drop. HPHX can be used for i) exchange of heat between fresh outdoor air and conditioned return air (heat recovery application) and ii) enhancing the dehumidification capability of cooling coil as well as reheat savings (dehumidification enhancement with reheat application). The operating limits of HPHX include capillary limit, boiling limit, entrainment limit, sonic limit and viscous limit. These limits determine the heat transfer capacity of HPHX. The length of pipe, diameter of pipe, properties of working fluid, structure of wick and angle of inclination of pipe are the influencing parameters that affects the operating limits of HPHX. The paper compares the operating limits for three working fluids: water, methanol and ethanol for air conditioning application. The performance of HPHX for these working fluids for different mesh geometry is studied using MATLAB programme. The results reveal that water gives the best performance for the given conditions.

Keywords— **Air conditioning, Heat pipe heat exchanger, MATLAB, Operating limits, Working fluids**

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I. INTRODUCTION

Heat pipe is the device which utilizes the latent heat of vaporization to transfer heat from one end to another with very small temperature difference. It has several effective conductivity as the hundred times that of equivalent to solid copper. Heat pipe does not require any external force for heat transfer which makes it as outstanding device of heat transfer. The schematic representation of heat pipe is as shown in fig.

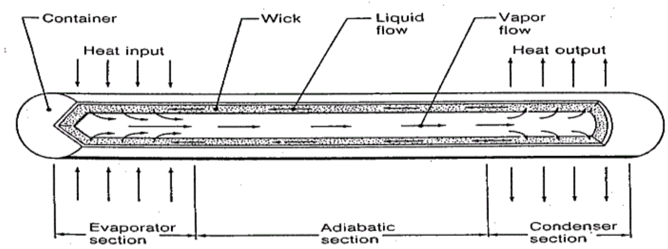


Fig1: Components of Heat Pipe [2]

Heat pipe consist of a closed container, tube or chamber of different shapes and sizes which has inner surface is lined with a porous capillary wick. The wick is filled with liquid phase of working fluid and the remaining part of tube is occupied by the vapor phase. In some cases there is only two phase working fluid is there in the tube and the wick is absent in it such heat pipe is known by the thermosyphon.

Basically heat pipe works on the temperature difference concept which consist of the three sections evaporative where evaporation of working fluid takes place i.e. phase change process takes place and in adiabatic section no heat losses happens which means that ideal phase is adiabatic section and in last condensation section the vapors condensate and moves down by gravitational force or capillary action. In this way the heat transfer takes place in heat pipe.

When heat is applied at the bottom (evaporative section) of heat pipe vaporization of working fluid takes place. During this phase change process, the fluid takes the latent heat of vaporization. This happens because of temperature of vapors in evaporative section is at high and hence at high pressure than the vapors in the condenser, the rise and flow of vapors at top of pipe (condenser section) where it gives the latent heat of vaporization. Gravitational force helps the condensed fluid to flow back to the bottom (evaporative section) of the pipe where it can again vaporize. Although the inner surface of heat pipe is lined with the grooves or porous structure to increase return flow rate of fluid from top to bottom section of heat pipe or for increasing the heat transfer coefficient.

In some cases utilization of capillary wick structure is there this is for the flow of liquid from the top side to bottom side (condenser section to evaporative section) of heat pipe. Due to the capillary wick the usage of heat pipe is in horizontal orientation, microgravity environments or applicable where the capillary structure must be pumped working fluid against the gravity from bottom to top of heat pipe.

Heat pipe heat exchanger (HPHX) is an excellent device used for heat recovery in air conditioning systems. Among the many outstanding advantages of using the heat pipe as a heat transmission device are constructional simplicity, exceptional flexibility, accessibility to control and ability to transport heat at high rate over considerable distance with extremely small temperature drop. HPHX can be used for i) exchange of heat between fresh outdoor air and conditioned return air (heat recovery application) and ii) enhancing the dehumidification capability of cooling coil as well as reheat savings (dehumidification enhancement with reheat application). The operating limits of HPHX include capillary limit, boiling limit, entrainment limit, sonic limit and viscous limit. These limits determine the heat transfer capacity ofHPHX. The length of pipe, diameter of pipe, properties of working fluid, structure of wick and angle of inclination of pipe are the influencing parameters that affects the operating limits of HPHX.at pipe is the device which utilizes the latent heat of vaporization to transfer heat from one end to another with very small temperature difference. It has several effective conductivity as the hundred times that of equivalent to solid copper. Heat pipe does not require any external force for heat transfer which makes it as outstanding device of heat transfer. The schematic representation of heat pipe is as shown in fig.

II.OPERATING LIMITS OF HEAT PIPE HEAT EXACHANGER

The operating limit of heat pipe is the excessive heat that transferred from one end to another under certain isothermal conditions. If heat is added to heat pipe above its limit, than the vapor-liquid cycle inside heat pipe becomes unsteady and at last the evaporator section become dry. Because of dryness it will failed to supply liquid so that heat pipe cannot continue transfer heat. The heat transfer rate is depends on some properties like thermo-physical properties of working fluid, wick structure, numbers of mesh etc. The operating limits of heat pipe are;

- Capillary Limit
- Viscous Limit
- Entrainment Limit
- Sonic Limit
- Boiling Limit

For the performance of the heat pipe determining factor is needed which are operating temperatures, and environmental conditions. For example, at lower operating temperatures, viscous limit becomes important but at normal operating temperatures, capillary limit is more important and at some higher temperatures, other limits become important for the performance of the heat pipe. The transition points between these limits depend on the type of working fluid used in the heat pipe. [3]

a. Capillary Limit:

The fundamental phenomenon of capillary limit in heat pipe todeveloped the capillary pressure difference throughout the vapor-liquid interface in condenser and evaporator section. When the capillary pressure decreases the liquid flow also decreases in condenser and evaporator section, due to this insufficient supply of liquid the wick in evaporator dry out. Therefore for continuous circulation of the working fluid, capillary pressure difference must needed for driving potential and the sum of all pressure losses inside the heat pipe must be less than the maximum capillary pressure.

The capillary limit is the net capillary forces created inside the condenser and evaporator section by the liquid interface should not be greater to overcome the frictional pressure losses due to fluid flow. Due to this the evaporator section becomes dry and the heat transfer process stops in condenser and evaporator section.

The capillary limit for heat pipe is expressed as;[1]

$$q_c = \frac{(\Delta P_{c,m} - \Delta P_{+})}{(\Delta P_v + \Delta P_l)}$$

Where,

$\Delta P_{c,m}$ = Capillary pumping pressure = $\frac{2.\sigma}{r_c}$

σ = Surface tension of fluid

r_c = Effective capillary radius of the wick

ΔP_{+} = Normal hydrostatic pressure losses = $\rho_l.g.d_v.\cos\psi$

ρ_l = Density of liquid

g = Gravity

d_v = Diameter of vapor space

ψ = Tilt angle

ΔP_v = Viscous pressure losses in liquid = $\frac{16.\mu_v.L_{eff}.}{2.r_{h,v}.A_v.\rho_v.\lambda}$

μ_v = Viscosity of vapor

L_{eff} = Effective length of vapor

$r_{h,v}$ = Hydraulic radius of the vapor space

A_v = Area of vapor space

ρ_v =Density of vapor

λ =Latent heat of vaporization

ΔP_l =Inertial and viscous pressure losses in liquid = $\frac{\mu_l}{K.A_w.\lambda.\rho_l}.L_{eff}$

μ_l = Viscosity of liquid

K =Permeability of liquid

A_w = Area of wick

ρ_l = Density of liquid

b. Viscous Limit:

The viscous limit depends on the vapor pressure of working fluid and the pressure losses due to viscous in vapor region. The force which drives the vapor in the evaporator and condenser region is called as pressure of vapor or vapor pressure. When the vapor pressure is less than the viscous losses in the vapor phase, than the cycle of vapor stops so that the heat pipe stops working. This limit is effective at the low temperature where the pressure of vapor is very low. Viscous limit is effective for all the section of heat pipe, since it depends on the vapor pressure gradient in condenser and evaporator section.The viscous limit can be express as;[1]

$$q_v = d_v{}^2.\lambda.A_v.\frac{P_v.\rho_v}{64.L_{eff}.\mu_v}$$

Where,

P_v = Vapor Pressure

c. Entrainment Limit:

In a heat pipe, working fluid is of tow phase – liquid and vapor - present at the same time. In the adiabatic section of the heat pipe, vapor flow to condenser through the pipe and liquid flow to evaporator through the wick structure. In two phase flow an interface between liquid and vapor flows occurs at certain point.

In the heat pipe, a viscous shear force occurs at the liquid-vapor interface due to counter flow of liquid and vapor. While operating the heat pipe, if the liquid surface tension force becomes less than viscous shear forces, the liquid particles will be interrupting the vapor flow. This interruption is called as the entrainment limit. This causes liquid loss in evaporator and it became dry. Due to this evaporator section becomes dry and heat pipe stops working. The mathematical expression presented by Cotter (1967) [1] for entrainment limit is;

$$q_e = A_v.\lambda\left(\frac{\sigma.\rho_v}{2.r_{h,w}}\right)^{1/2}$$

Where,

$r_{h,w}$ =Hydraulic radius of wick

1.4. Sonic Limit:

When vapor flow velocityreaches to sonic flow velocity at the end part of the evaporator section. Due toincrease in vapor velocity at theevaporator end, the flow becomes choked flow so; the mass flow of the vapor is lessthan critical mass flow at choked flow conditions. Therefore, the rate heat transfer becomes lesser and higher heat cannot be transferred to required section. Sonic limit does not cause a failure like dry-out in heat pipe. It only restricts the capacity of the heat pipe. Sonic limit is effective at lower operating temperatures. Like capillary and viscous limits, sonic limit is also effective for the entire heat pipe.

The mathematical formula for the sonic limit is found by Levy (1968) [1] as follows;

$$q_s = 0.474.\lambda.A_v.(\rho_v.P_v)^{1/2}$$

d. Boiling Limit:

The Boiling limit is caused by the bubble formation in the wick structure in evaporator section. The nucleate boiling occurs during the evaporation process in the evaporator section.As the input of heat increases, nucleate boiling further converted into film boiling. Due to the film boiling it restrict liquid return to evaporator section and less liquid flow into evaporator sectionso that the evaporator section became dry. The main parameters of bubble formation theory are the number and size of the nucleation sites and the temperature gradient of fluid and pipe wall.

The maximum heat flux can be expressed as;[1]

$$q_b = \left(\frac{2.\pi.L_e k_{eff}.T_v}{\lambda.\rho_v.\ln\left(d_i/d_v\right)}\right).\left(\frac{2.\sigma}{r_n} - \Delta P_{c,m}\right)$$

Where,

L_e = Evaporator length

k_{eff} = Effective thermal conductivity of the liquid-wick combination

T_v = Vapor temperature

d_i = Inner diameter of pipe

d_v =Diameter of vapor space

r_n =Critical nucleation site radius

$\Delta P_{c,m}$ = Maximum capillary pressure difference

III. COMPRATIVE INVESTIGATIONS OF OPERATING LIMITS FOR DIFFERENT WORKING FLUIDS

The parameters for analysis of heat pipe are mentioned in Table 3.1.

Wick type	**Wire screen mesh**
Mesh number	**i. 180 mesh/in** **ii. 250 mesh/in**
Wire diameter	**0.04×10^{-3} m**

Working Fluid type	**i. Water** **ii. Methanol** **iii. Ethanol**
Temperature Range	**20°C - 40°C**

Table 3.1- Parameters for analysis of heat pipe

The investigation is done for all the parameters given above to see the direct effect of parameter, while others are constant. The MATLAB program is prepared for the operating limits. The program can be done for two purposes;

a) General analysis to see the effects of mesh numbers on heat transfer capacity of heat pipe.

b) To obtain the heat transfer capacity of a heat pipe for different working fluids at different working conditions.

3.1. Analysis for wire meshes of 180 mesh/in:

The specification of the heat pipe is mention in table 3.2.

Diameter	**9.5mm**
Length	**650 mm**
Evaporative length	**300 mm**
Condenser length	**300 mm**
Adiabatic length	**50 mm**
Wall thickness	**0.75 mm**
Pipe material	**Copper**
Wick material	**Phosphorus bronze**
Orientation	**Horizontal**
Wick structure	**Wire screen**
Number of meshes	**i. 180 mesh/in** **ii. 250 mesh/in**
Wire diameter	**0.04×10^{-3} m**
Number of layers	**2**

First analysis is performed for the 180 mesh/in with water, methanol and ethanol as working fluid. The calculations are done with the help of MATLAB program at different operating temperature, some results are obtained and these calculated results are plotted in graphical form, are mention below;

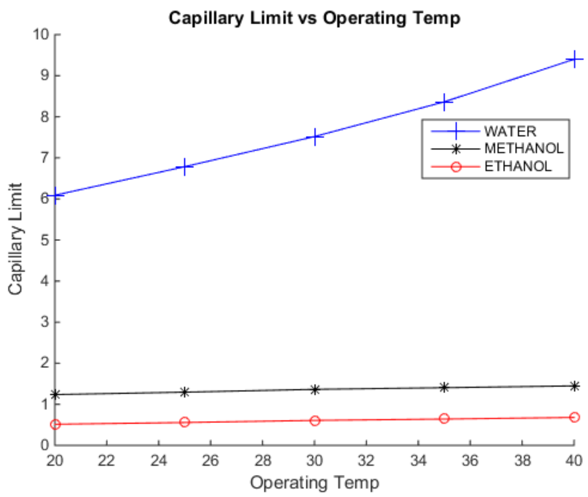


Fig 3.1.1- Comparison of Capillary limit for 180 mesh

As shown in fig 3.1.1 the three main working fluids are compared i.e. water, methanol and ethanol. The graph shows that as the operating temperature increases capillary limit also increases for water as working fluid. This increase in capillary limit happens due to increase in capillary pressure. But the limit partially increases for methanol and ethanol as working fluid. This means that for selected range (20-40°C) of operating temperature water is good as working fluid in HPHX.

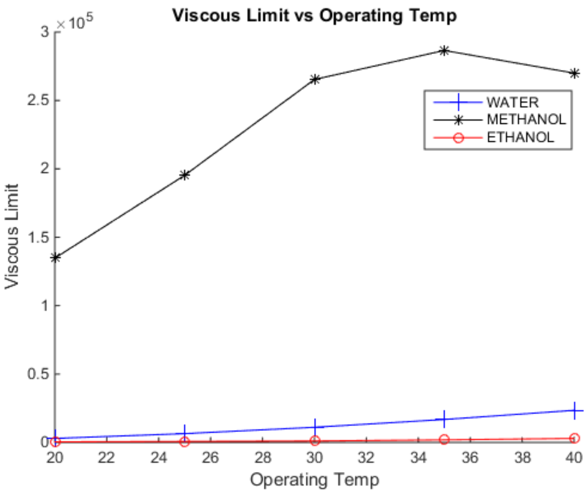


Fig 3.1.2- Comparison of Viscous limit for 180 mesh

The comparison of water, methanol and ethanol working fluid is shown in fig 3.1.2. The graph indicates that the viscous limit is so high for methanol as compared to the water and ethanol. This means that as the operating limit increases the viscous limit also goes on increasing. In this case methanol is good working fluid for 180 mesh/inch in HPHX for viscous limit.

From this graph shown in fig 3.1.3 it can be observe that the entrainment limit for all three working fluids increases with operating temperature, rate of increase for water is high as compared to other working fluids.In this case water is good working fluid for 180 mesh/inchin HPHX for entrainment limit.

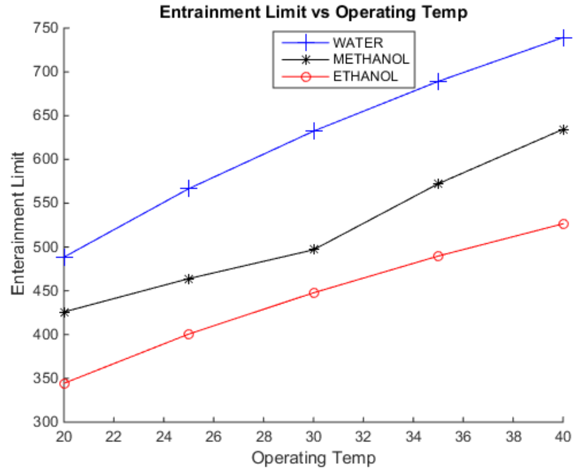


Fig 3.1.3- Comparison of Entrainment limit for 180 mesh

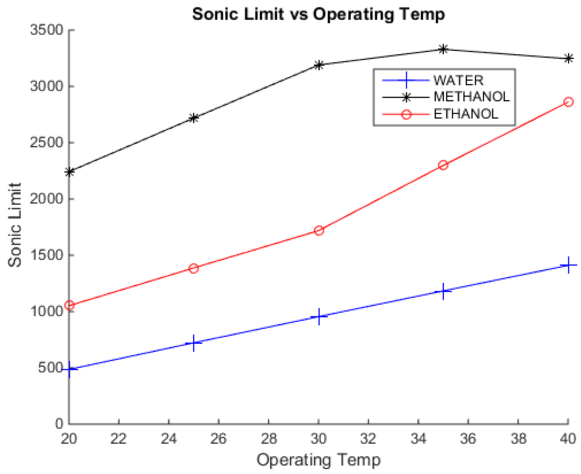


Fig 3.1.4- Comparison of Sonic limit for 180 mesh

Sonic limit increases with respect to the operating temperatures. In case of water rise is steady and low. Methanol shows highest sonic limit as compare to other two. In case if methanol sonic limit increase till particular limit and then falls down. For ethanol rise in limit is steady till 30ºC then sudden hike is observe. So that methanol becomes good working fluid for 180 mesh/inch in sonic limit for HPHX. The sonic limit's graph is shown in figure 3.1.4.

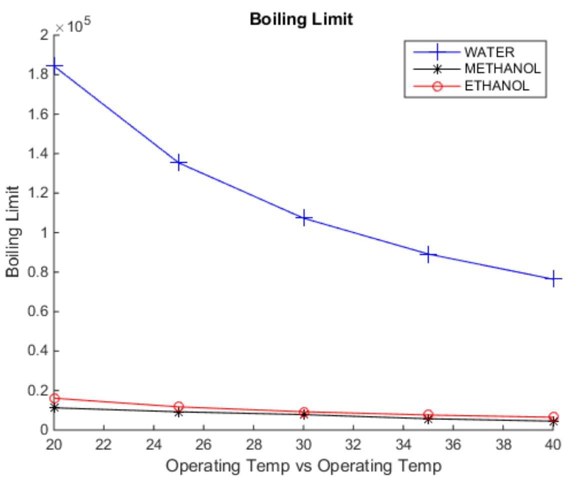


Fig 3.1.5 - Comparison of Boiling limit for 180 mesh

In case of boiling limit as the operating temperature increases the boiling limit deceases gradually. This decrease in limit happens due to decrease in bubble formation inside the heat pipe. In this case water becomes high value caring working fluid as compared to other two fluids. For ethanol and methanol the value of boiling limit is high at 20ºC then its decreases steadily. For boiling limit water is good working fluid at 180 mesh/inch in HPHX. Figure 3.1.5 shows the comparison of different working fluid for boiling limit.

3.2. Analysis for wire meshes of 250 mesh/inch:

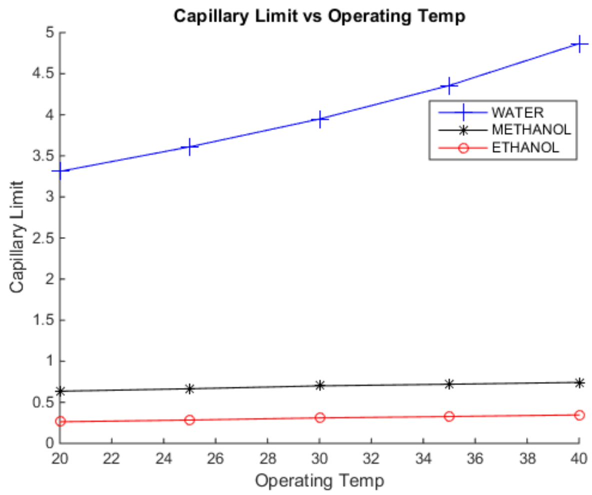


Fig 3.2.1- Comparison of Capillary limit for 250 mesh

As shown in fig 3.2.1 the three main working fluids are compared i.e. water, methanol and ethanol. The graph shows that as the operating temperature increases capillary limit also increases for water as working fluid. This increase in capillary limit happens due to increase in capillary pressure.But the limit partially increases for methanol and ethanol as working fluid. This means that for selected range (20-40ºC) of operating temperature water is good as working fluid in HPHX.

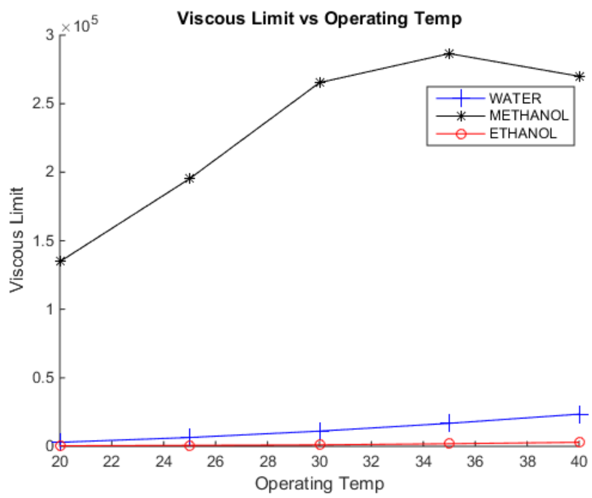


Fig 3.2.2 - Comparison of Viscous limit for 250 mesh

The comparison of water, methanol and ethanol working fluid is shown in fig 3.2.2. The graph indicates that the viscous limit is so high for methanol as compared to the water and ethanol. This means that as the operating limit increases the viscous limit also goes on increasing. In this case methanol is good working fluid for 250 mesh/inch in HPHX for viscous limit.

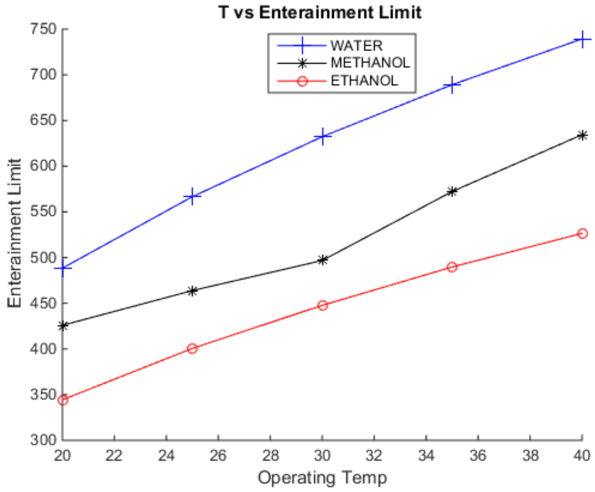
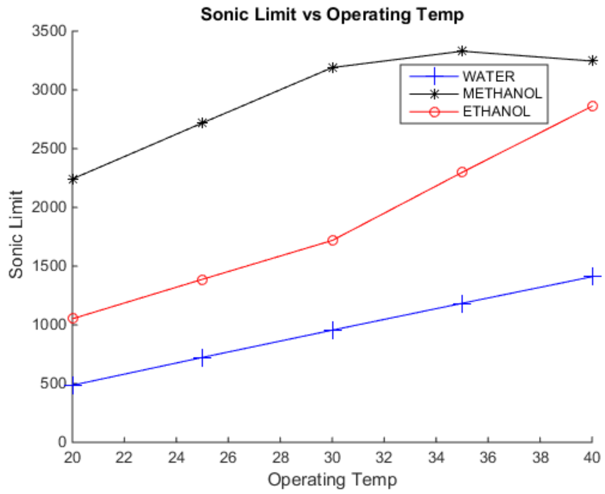


Fig 3.2.3- Comparison of Entrainment limit for 250 mesh

From this graph shown in fig 3.2.3 it can be observe that the entrainment limit for all three working fluids increases with operating temperature, rate of increase for water is high as compared to other working fluids. In this case water is good working fluid for 250 mesh/inch in HPHX for entrainment limit.



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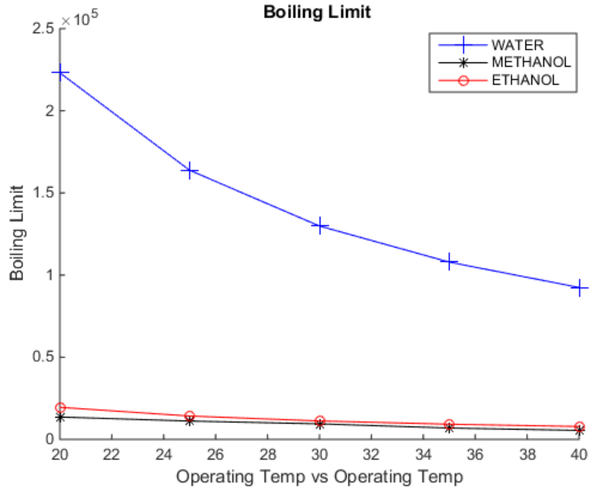

Fig 3.2.5- Comparison of Boiling limit for 250 mesh

V.CONCLUSION

The paper analysis the operating limits of heat pipe heat exchanger for air conditioning application with the help of MATLAB software. It is observed that the water has higher heat transfer rate for selected operating temperature range i.e. 20º C - 40 ºC. The results of heat pipe heat exchanger are comparatively better at 180 mesh than 250 mesh.

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