International Journal of Research (IJR)
e-ISSN: 2348-6848, p- ISSN: 2348-795X Volume 2, Issue 08, August 2015
Available at http://internationaljournalofresearch.org

Analysis of a Heat Pipe to Obtain Maximum Heat Transfer Rate

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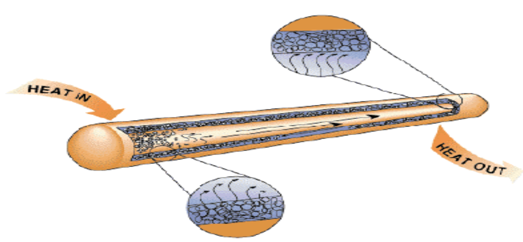
ABSTRACT
Maximum heat transfer rate is an important parameter in heat pipe performance. In the present study the maximum heat transfer rate has been calculated by using C++ program for the different operating temperature of a particular heat pipe dimension. For this purpose the selected fluids is water. Taking the dimension as constant and varying the temperature, the maximum heat transfer rate has been calculated.

Keywords: Heat Pipe; Max Heat Transfer Rate; Second Law of Thermodynamics; Entropy Generation; C++ Program; Algorithm

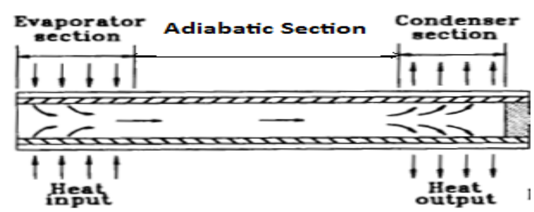
1. INTRODUCTION

A heat pipe is a simple device that can quickly transfer heat from one point to another. They are often referred to as the "superconductors" of heat as they possess an extraordinary heat transfer capacity & rate with almost no heat loss.



1.1. CONSTRUCTION

It consists of a sealed aluminium or copper container whose inner surfaces have a capillary wicking material. Heat pipe is divided in three regions along its length. These regions are: Evaporator region Adiabatic region Condenser region

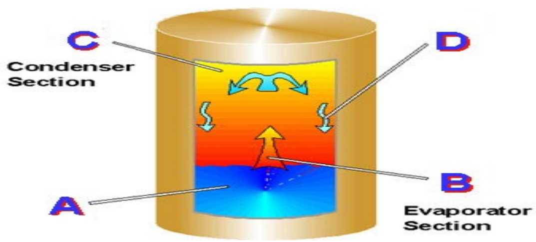


1.2. WORKING PRINCIPLE

Liquid (Inside the container) under its own pressure enters the pores of the capillary material, wetting all internal surfaces.

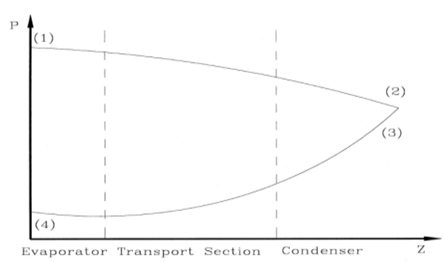
Applying heat along the surface of the heat pipe causes the liquid at that point to boil and enter a vapor state.

The gas, which then has a higher pressure, moves inside the sealed container to a colder location where it condenses thus giving up the latent heat of vaporization.



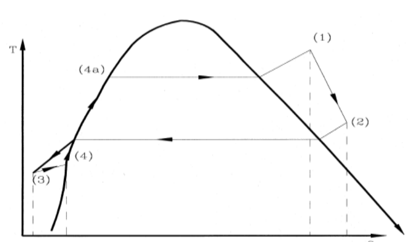
A. Heat is absorbed in the evaporating section.
B. Fluid boils to vapor phase.
C. Heat is released from the upper part of cylinder to the environment; vapor condenses to liquid phase.
D. Liquid returns by to the lower part of cylinder (evaporating section).

1.3. Pressure Variation along a Steady-State Heat Pipe



Pressure variation along a steady-state heat pipe.

1.4. Thermodynamic Cycle of a Heat Pipe Working Fluid

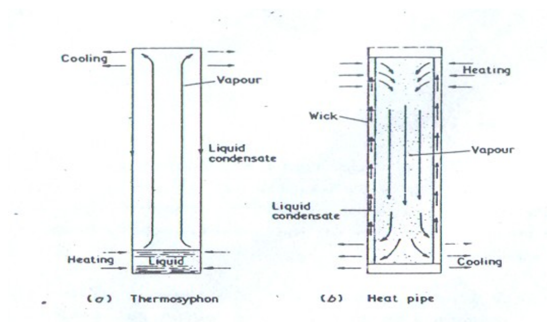


Thermodynamic cycle of a heat pipe working fluid.

1.5. DIFFERENCE BETWEEN HEAT PIPE AND THERMOSYPHON

Heat Pipe can transport heat against gravity by an evaporation-condensation cycle with the help of porous capillaries that form the wick. The wick provides the capillary driving force to return the condensate to the evaporator. This is not possible in Thermosyphon.

In Thermosyphon evaporator always must be below condenser region but in heat pipe there is no such type of condition.



2. PRACTICAL DESIGN CONSIDERATIONS

The three basic components of a heat pipe are:

1. the container
2. the working fluid
3. the wick or capillary structure

In order to design and fabricate heat pipe , a suitable combination of these three components is very necessary .

2.1. The Container

The function of the container is to isolate the working fluid from the outside environment.

It must:

1. be leak-proof
2. maintain the pressure differential across its walls
3. enable transfer of heat to take place from and into the working fluid.

International Journal of Research (IJR)
e-ISSN: 2348-6848, p- ISSN: 2348-795X Volume 2, Issue 08, August 2015
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2.1(i) Selection of the container material depends on many factors. These are as follows:

- Compatibility: The container should be compatible with working fluid and external environment. The two major results of incompatibility are corrosion and the generation of non condensable gas.
- Strength to weight ratio: A high strength to weight ratio is more important in spacecraft applications. The material should be non-porous to prevent the diffusion of vapor.
- Thermal conductivity: A high thermal conductivity ensures minimum temperature drop between the heat source and the wick.
- Ease of fabrication, including welding, mach inability and ductility
- Porosity
- Wet ability

2.2. The working fluid

A first consideration in the identification of a suitable working fluid is the operating vapour temperature range. Within the approximate temperature band, several possible working fluids may exist, and a variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered.

2.2(i) The prime requirements of working fluid are:

- compatibility with wick and wall materials
- good thermal stability
- wet ability of wick and wall materials
- vapor pressure not too high or low over the operating temperature range
- high latent heat
- high thermal conductivity
- low liquid and vapor viscosities
- high surface tension
- acceptable freezing point

2.3. Wick or Capillary Structure

- The prime purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator.
- It must be able to distribute the liquid around the evaporator section to any area where heat is likely to be received by the heat pipe.
- The selection of the wick for a heat pipe depends on many factors, several of which are closely linked to the properties of the working fluid.

3. THEORY OF HEAT PIPE

In order for the heat pipe to operate the maximum capillary pumping head (ΔPc) max must be greater than the total pressure drop in the pipe.

$(\Delta Pc)\ max >= \Delta Pl + \Delta Pv + \Delta Pg$

Where

ΔPl is the pressure difference in liquid phase.

ΔPv is the pressure difference in vapor phase.

ΔPg is gravitational head.

- The pressure drop ΔPl is required to return the liquid from the condenser to the evaporator.
- The pressure drop ΔPv is necessary to cause the vapor to flow from the evaporator to the condenser.
- The gravitational head ΔPg which may be zero, positive or negative.

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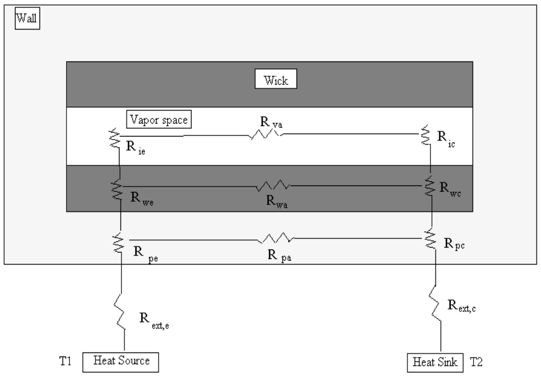
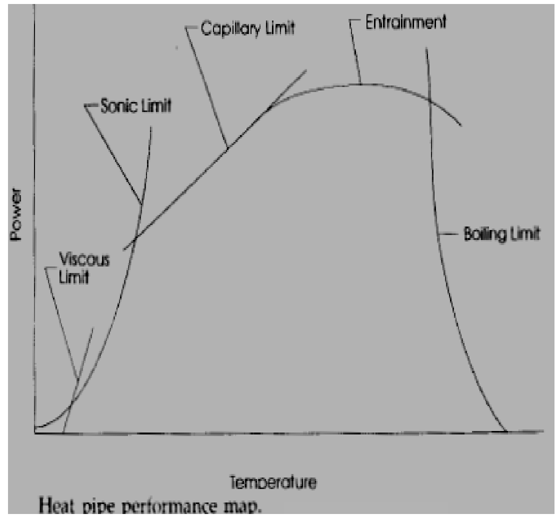
3.1. HEAT TRANSFER AND TEMPERATURE DIFFERENCE IN HEAT PIPES

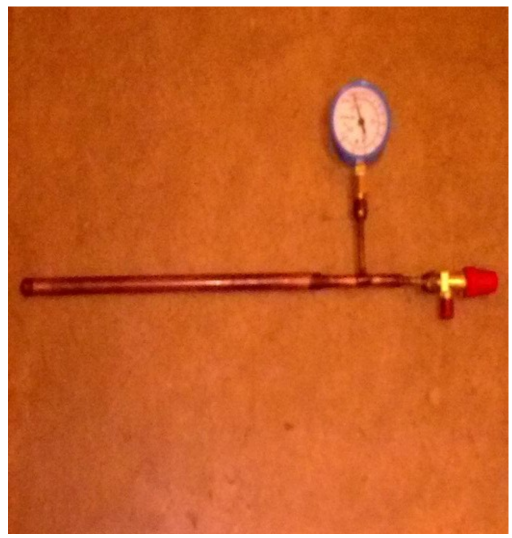


3.2. LIMITS TO HEAT TRANSPORT

- *Entrainment Limit-* at high vapor velocities, droplets of liquid in the wick are torn from the wick and sent into the vapor. Results in dry out.
- *Sonic limit-* occurs when the vapor velocity reaches sonic speed at the evaporator and any increase in pressure difference will not speed up the flow; it seems as if choking has occurred.
- *Viscous Limit-* at low temperatures the vapor pressure difference between the condenser and the evaporator may not be enough to overcome viscous forces. The vapor from the evaporator doesn't move to the condenser and the thermodynamic cycle doesn't occur.
- *Boiling Limit-* occurs when the radial heat flux into the heat pipe causes the liquid in the wick to boil and evaporate causing dry out.
- *Capillary limit-* occurs when the capillary pressure is too low to provide enough liquid to the evaporator from the condenser. Leads to dry out in the evaporator. Dry out prevents the thermodynamic cycle from continuing and the heat pipe no longer functions properly.

3.3.Heat Pipe Performance Map





4. HEAT PIPE DESIGN

- **The container :** A copper tube
- **The working fluid :** Distilled Water
- **The wick or capillary structure:** Stainless Steel mesh.

4.1. COMPATIBILITY DATA

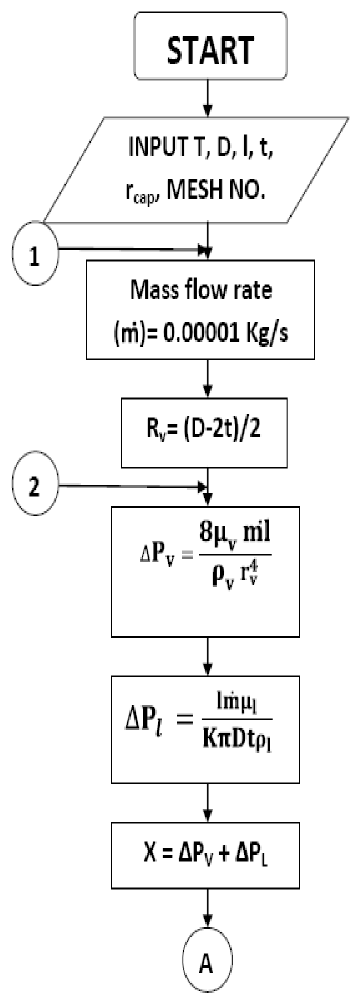
WORKING FLUID	COMPATIBALE MATERIAL	INCOMPATIBALE MATERIAL
WATER	STAINLESS STEEL, COPPER, NICKEL, SILICA	ALUMINIUM, INCONEL
METHANOL	STAINLESS STEEL, COPPER, NICKEL, BRASS	ALUMINIUM
AMMONIA	ALUMINIUM, STAINLESS STEEL, COLD ROLLED STEEL, IRON	COPPER
ACETONE	ALUMINIUM, STAINLESS STEEL, COPPER, NICKEL	

REF. FAGHIRI, 1995

4.2.Design Parameters:

- **Length of copper tube l= 300 mm**
- **ID of tube d = 10 mm**
- **Mesh No. = 250**
- **Thickness t = 0.18 mm**
- **Permeability of mesh K= 0.0000302 mm^2**
- **Pore Radius rcap = 0.02 mm**
- **Critical Temperature of fluid(here water) T= 647.3 K**
- **Minimum Heat Transferred = 20W**

4.3. FLOW CHART



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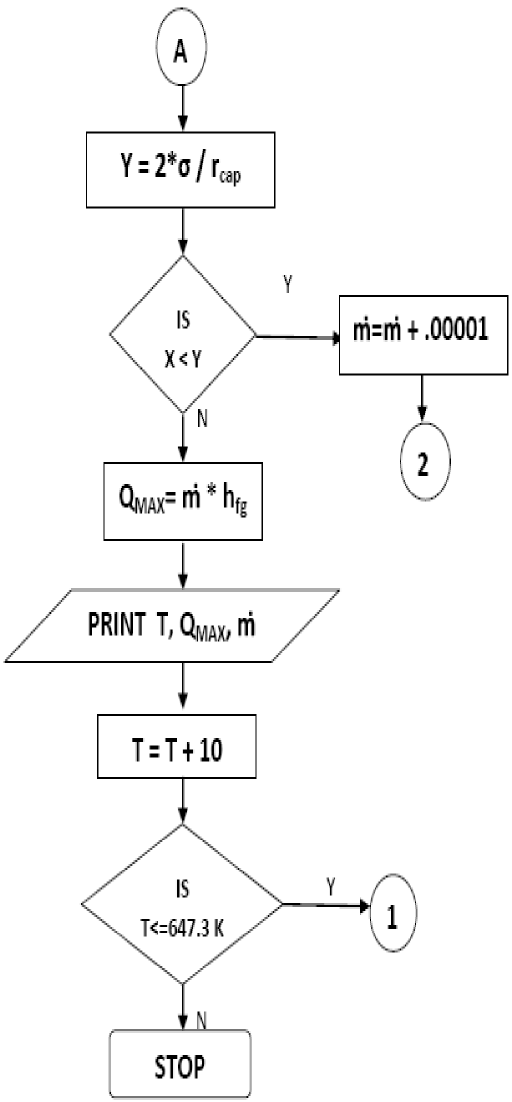

4.4. Program in C++:

```
#include<iostream.h>
#include<conio.h>
#include<math.h>
float vapvis(float);
float vapden(float);
float liqvis(float);
float liqden(float);
float latent(float);
float surften(float);
int main()
{
clrscr ();
int M;
char x;
float l,D,T,t,r,K,X,Y,Pv,Pl,Pg,m,Re,VV,VD,LV,LD,LH,ST,ang,an;
cout<<"Enter the length and diameter in mm of heat pipe"<<endl; cin>>l>>D;
cout<<"enter the temperature in kelvin "<<endl;
cin>>T;
cout<<"enter the mesh number, thickness of wick section(mm), pore radius(mm), wick permeability"<<endl;
cin>>M>>t>>r>>K;
cout<<"enter angle in degrees with horizontal"<<endl;
cin>>an;
if (an! =0)
{
cout<<"Is condenser above evaporator? if yes then press y(case sensitive)"<<endl;
cin>>x;
}
Float Rv= (D-2*t)/2; ang=an*3.141592/180;
if (x=='y')
{
```

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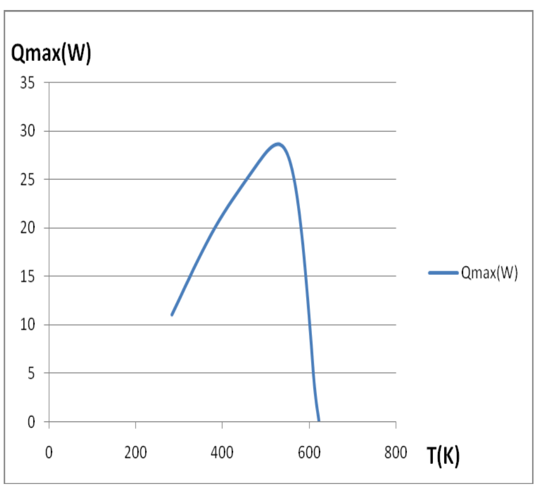
```
ang=ang*(-1);
}
while (T<=647.3)
{
VV=vapvis(T);
VD=vapden (T);
LD=liqden(T);
LV=liqvis(T);
LH=latent (T);
ST=surften(T);
m=.0000001;
do
{
Y=2*ST*1000/r;
Re=(4*VV*m*1000)/(pow(VD,2)*3.14*(D-2*t)); if(Re<2100.00) //flow is laminar
{
Pv=(8*VV*m*l*pow(10,9))/(VD*pow(Rv,4));
}
else
{
float f=.0791/pow(Re,.25);
Pv=(32*f*m*m*l*pow(10,12))/(3.14*3.14*VD*pow((D-2*t),5));
}
Pl=(LV*l*m*pow(10,9))/(LD*K*3.14*(D-2*t)*t);
Pg=LD*9.81*l*.001*sin(ang);
X=Pv+Pl+Pg;
m=m+.00000001; } while(X<Y);
float Qmax= (m-.00000001)*LH;
cout<<" Max. heat flow rate at temp "<<T<<" is "<<Qmax<<endl<<endl;
T=T+10.0;
}
getch();
}
float vapvis(float T)
{
float a=1.863533364888E-10*pow(T,2) - 1.093174408548E-07*T + 2.503537432010E-05; return a;
}
float vapden(float T)
{
float b=2.465052098940E+02*pow(T,-1.017763280122E+00); return b;
}
float liqvis(float T)
{
float c=1.794037761063E+06*pow (T,-3.756123222676E+00);
return c;
}
float liqden(float T)
{
float d=2.313127868709E-07*pow(T,4) - 2.847655191040E-04*pow(T,3) + 1.270517279667E-01*T*T - 2.458102900740E+01*T + 2.751294205932E+03;
return d;
}
```

```
float latent(float T)
{
float e=-1.153092196908E-08*pow(T,6) +
2.957326884464E-05*pow(T,5)-
3.116886877126E-02*pow(T,4) +
1.724864190563E+01*pow(T,3) -
5.283238375547E+03*pow(T,2) +
8.468846719554E+05*T -
5.283675247708E+07;
return e;
}
float surften(float T)
{
float w=-9.195841005759*pow(10,-8)*T*T-
1.241539247906*pow(10,-
4)*T+1.171567879488*pow(10,-1);
return w;
}
```

4.5.GRAPH BETWEEN QMAX AND T



5. CALCULATIONS

In order for the heat pipe to operate the maximum capillary pumping head (Pc)max must be greater than the total pressure drop in the pipe. This pressure drop is made up of three components.

a) The pressure drop P_l required to return the liquid from the condenser to the evaporator.

b) The pressure drop P_v necessary to cause the vapor to flow from the evaporator to the condenser.

c) The gravitational head P_g which may be zero, positive or negative.

Thus

$(\Delta P_C)_{max} >= \Delta P_L + \Delta P_V + \Delta P_G$

If this condition is not met, the wick will dry out in the evaporator region and the pipe will not operate.

5.1.CAPILLARY PRESSURE ΔPc:

Pressure drop across a curved liquid interface is

$\Delta P = 2\sigma_l /R$

$R\cos\theta = r$

Where r is the effective radius of the wick pores and θ the contact angle. Hence the capillary head at the evaporator

$$\Delta P_e = 2\sigma_l\left(\frac{\cos\theta_e}{r_e}\right)$$

Similarly at the condenser

$$\Delta P_c = 2\sigma_l\left(\frac{\cos\theta_c}{r_c}\right)$$

The resultant capillary head will be

$$\Delta P_c = 2\sigma_l\left(\frac{\cos\theta_e}{r_e} - \frac{\cos\theta_c}{r_c}\right)$$

This will have a maximum value when
$\cos\theta_e = 1$ and $\cos\theta_c = 0$.

Hence $(\Delta P_c)_{max} = \frac{2\sigma_1}{r_e}$

5.2.PRESSURE DIFFERENCE DUE TO FRICTION FORCES:

In this section we will consider the pressure differences in the liquid and vapor phases which are caused by frictional forces.

Laminar Flow - the Hagen Poiseuille equation: The steady state laminar flow of an incompressible fluid of constant viscosity μ, through a tube of circular cross section, radius a, is described by the Hagen-Poiseuille equation.This equation relates the velocity v_r of the fluid, at radius r, to the pressure difference P_2-P_1 across a tube length l.

$$v_r = \frac{a^2}{4\mu}\left[1 - \left(\frac{r}{a}\right)^2\right]\frac{P_2 - P_1}{l}$$

Turbulent Flow – the Fanning equation: The pressure drop for turbulent flow is usually related to the average velocity by the Fanning equation:

$$\frac{P_2 - P_1}{l} = \frac{4}{d}f\frac{1}{2}\rho v^2$$

Where f is the fanning factor.

f is related to Reynold's number and in the turbulent region is given by the Blasius equation:

$$f = \frac{0.0791}{Re^{0.25}} \quad , 2100 < R_e < 10^5$$

We see that if we write $f = \frac{16}{Re}$ for Re < 2100 the fanning equation reduces to the Hagen-Poiseuille form.

5.3.PRESSURE DIFFERENCE IN THE LIQUID PHASE ΔPl:

The flow regime in the liquid phase is almost always laminar. Since the liquid channels will not in general be straight nor of circular cross-section and will often be interconnected the Hagen-Poiseuille equation must be modified to take account of these differences.

It is usual for homogenous wick structure to use Darcy's Law for the calculation of ΔP_l.

Darcy's Law is written as

$$\Delta P_1 = \frac{\mu_1 l\dot{m}}{\rho_1 KA}$$

Where K is the wick permeability
A is the wick cross sectional area

5.4.PRESSURE DIFFERENCE IN VAPOR PHASE ΔPv:

The total vapour phase difference in pressure will be the sum of the pressure drops in the three regions, namely the evaporator drop ΔP_{ve} the adiabatic section drop ΔP_{va}, and the pressure drop in the condensing region ΔP_{vc}.

In the evaporator region the vapor pressure gradient will be necessary to carry out two functions.

1. To accelerate the vapour entering the evaporator section up to the axial velocity v. Since on entering the evaporator this vapour will have radial velocity but no axial velocity. The necessary pressure gradient will be termed as the inertial term ΔP_V'.

2. To overcome frictional drag forces at the surface $r=r_v$ at the wick. This is the viscous term $\Delta P_v''$.

$$\Delta P_v' = \rho v^2$$

$$\Delta P_v'' = \left(\frac{8\mu_v \dot{m}}{\pi r_v^4}\right)\frac{l_e}{2}$$

Hence

$$\Delta P_{ve} = \Delta P_v' + \Delta P_v''$$

$$= \rho v^2 + \left(\frac{8\mu_v \dot{m}}{\pi r_v^4}\right)\frac{l_e}{2}$$

The condenser region may be treated in a similar manner, but in this case axial momentum will be lost as the vapour stream is brought to rest so the inertial term will be negative, that is there will be pressure recovery. For the simple theory the two inertial terms will cancel and the total pressure drop in the vapour phase will be due entirely to the viscous terms.

In the adiabatic region the pressure difference will contain only the viscous term which will be given either by the Hagen-Poiseuille equation or the Fanning equation depending on whether the flow is laminar or turbulent.

For Laminar Flow:

$$\Delta P_{va} = \frac{8\mu_v m}{\pi r_v^4} l_a$$

for $R_e \leq 2100$

For Turbulent Flow:

$$\Delta P_{va} = \frac{2}{r_v} f \frac{1}{2} \rho_v v^2 l_a$$

for $R_e > 2100$

where $f = \frac{0.0791}{R_e^{0.25}}$

Hence the total vapour pressure drop is given by:

$$\Delta P_v = \Delta P_{ve} + \Delta P_{vc} + \Delta P_{va}$$

$$= \rho v^2 + \frac{8\mu_v \dot{m}}{\pi r_v^4}\left[\frac{l_e + l_c}{2} + l_a\right]$$

for laminar flow and no pressure recovery

$$\Delta P_v = \frac{8\mu_v \dot{m}}{\pi r_v^4}\left[\frac{l_e + l_c}{2} + l_a\right]$$

for laminar flow with full pressure recovery.

5.5.GRAVITATIONAL HEAD:

The pressure difference due to the hydrostatic head of the liquid may either be positive, negative or zero, depending on the relative positions of the evaporator and condenser. This pressure difference ΔP_g is given by the expression

$$\Delta P_g = \rho_l g \sin\Phi$$

Where ρ_l is the liquid density

g is the acceleration due to gravity

l is the heat pipe length

ϕ the angle made by the heat pipe with the horizontal.(ϕ is positive when the condenser is lower than the evaporator)

5.6.LIMITS TO HEAT TRANSPORT:

Upper limits to the heat transport capability of a heat pipe may be set by one or more factors.

Viscous Limit: At low temperature viscous forces are dominant in the vapour flow down the pipe. Busse has shown that the axial heat flux rapidly increases as the pressure in the condenser is reduced, the maximum heat flux occurring when the pressure is reduced to the zero. Busse carried out a two dimensional

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analysis, finding that the radial velocity component had a significant effect, he derived the following equation

$$q = \frac{rL\rho_v P_v}{16\mu_v^l}$$

Where P_V and ρ_V evaporator end of the pipe.

This equation agrees well with published data.

Sonic Limit: At a somewhat higher temperature choking at the evaporator exit may limit the total power handling capability of the heat pipe.

The sonic limit is given by:

$q=0.474\ L\ (\rho_V\ p_V)^{1/2}$

There is good agreement between this formula and experimental results.

Entrainment limit: Following equation gives the entrainment limiting flux

$$q= \sqrt{\frac{2\pi\rho_V L^2\sigma_l}{Z}}$$

Kemme's experiments suggest a rough correlation of this failure mode with the centre to centre wire spacing for z, and that a very fine screen will suppress entrainment.

Capillary Limits, (wicking Limits). In order for the heat pipe to operate, equation must be

satisfied, namely

$\Delta P_{c\ max} > \Delta P_l + \Delta P_v + \Delta P_g$

An expression for the maximum flow rate m_{max} may readily be obtained if we assume

1. The liquid properties do not vary along the pipe

2. The wick is uniform along the pipe

3. The pressure drop due to vapour flow can be neglected.

$$m_{max} = \left[\frac{\rho_l\sigma_l}{\mu_l}\right]\left[\frac{KA}{l}\right]\left[\frac{2}{r_e} - \frac{\rho_l g l}{\sigma_l} sin\Phi\right]$$

And the corresponding heat transport Q_{max}

$Q_{max} = m_{max}L$

$$= \left[\frac{\rho_l\sigma_l L}{\mu_l}\right]\left[\frac{KA}{l}\right]\left[\frac{2}{r_e} - \frac{\rho_l g l}{\sigma_l} sin\Phi\right]$$

The group $\frac{\rho_l\sigma_l L}{\mu_l}$ depends only on the properties of the working fluid and is known as the figure of merit M.

Burnout: Burnout will occur at the evaporator at high radial fluxes. A similar limit on peak radial flux will also occur at the condenser. For water and other non metallics vapour production in the wick become important a lower flux densities (130 KW/m^2) and there are no simple correlation. Because of phase equilibrium at interface, liquid at the evaporator **is** always superheated to some degree, but it is difficult to specify the degree of superheated needed to initiate bubbles in the wick. While boiling is often taken as a limiting feature in wicks, possibly upsetting the capillary action, Cornwell and Nair found that nucleation reduces the radial temperature difference and increases heat pipe conductance. One factor in support of this is the increased thermal conductivity of liquid saturated wicks in evaporator section, compared with that in the condenser.

Time believed that the time limit will become effective only when the bubbles generated within the wick become trapped there, forming a

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vapor blanket. Thus, some enhancement of radial heat transferring the evaporator section can be obtained by nucleate boiling effects.

6. CONCLUSION

- Heat pipe is tested in horizontal orientation.
- Rate of max heat transfer through the heat pipe has been calculated at different operating temperature.
- A graph has been plotted between max heat transfer rate and operating temperature.
- By seeing the graph ,we can select the operating temperature to minimize entropy generation in heat pipe.
- Heat transferred through Heat Pipe is approximately **15 times** the heat transferred through pure conduction in heat pipe.

6.1. ADVANTAGES

- Simple Structure
- Relatively Inexpensive
- Insensitive to gravitational field
- Silent and Reliable in its operation

6.2.APPLICATIONS

1. Space Technology

- Spacecraft temperature equalization
- Component cooling, temperature control and radiator design in satellites.
- Other applications include moderator cooling, removal of heat from the reactor at emitter temperature and elimination of troublesome thermal gradients along the emitter and collector in spacecrafts.

2. Heat pipes for Dehumidification and Air conditioning

3. Notebook and mobile PCs thermal control.

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