Energy Conservation and Waste Heat Recovery

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Lecture – 39

Heat Pipe – Part III

Welcome friends. We will continue with our discussion on heat pipes if you recall last time we started by we started to derive an expression for the maximum amount of heat that can be pumped by a heat drive from it is evaporator to the condenser end and we named it is known as axial power rating.

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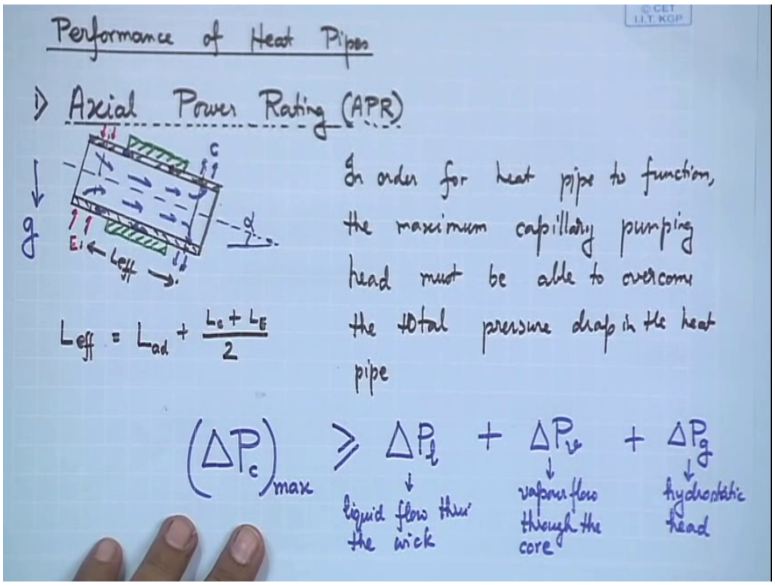

Performance of Heat Pipes

i) Axial Power Rating (APR)

In order for heat pipe to function, the maximum capillary pumping head must be able to overcome the total pressure drop in the heat pipe

$$L_{eff} = L_{ad} + \frac{L_c + L_E}{2}$$

$$(\Delta P_c)_{max} \geq \underset{\substack{\downarrow \\ \text{liquid flow thru'} \\ \text{the wick}}}{\Delta P_l} + \underset{\substack{\downarrow \\ \text{vapour flow} \\ \text{through the} \\ \text{core}}}{\Delta P_v} + \underset{\substack{\downarrow \\ \text{hydrostatic} \\ \text{head}}}{\Delta P_g}$$

So, if you recall we had drawn this schematic over here which I am showing and we say that in order for the heat pipe to function the maximum capillary pumping head, which is provided by the wick; must be able to overcome the total pressure drop of the fluid as it flows through the heat pipe and how does it flow it first vaporizes and then the vapor flows through the core comes to the other end where it condenses and then in the liquid form it flows back through the wick.

So, if I say that my maximum capillary force if I write that or the capillary pumping head, if I write it as delta P c and I say this max must be able to overcome. So, must be greater than equal to the different pressure drop that the fluid faces as it flows through the different sections of the heat pipe. So, what are those?

So, the first one I am going to write it as delta P l, what is delta p l this is for liquid flow through the wick. Then I will say delta P v why what is this is the vapor flow through the core what else see. This is where the inclination that I have gave deliberately of alpha comes into picture why because we also have a hydrostatic head because of gravity and I am going to talk call it as delta P g I would say hydrostatic head.

Now why is this important if you look at this diagram itself see as the liquid is pumped through the wick it also has to overcome the force due to gravity right, because the tendency of the liquid will be to come down along the direction of gravity and the capillary force pumping head has to prevent that also and force it to flow in the opposite direction right. So, that is the hydrostatic head clear.

So, what we are going to do next is we are going to look at expressions for each of them and then try to equate that starting with one by let us start one by one.

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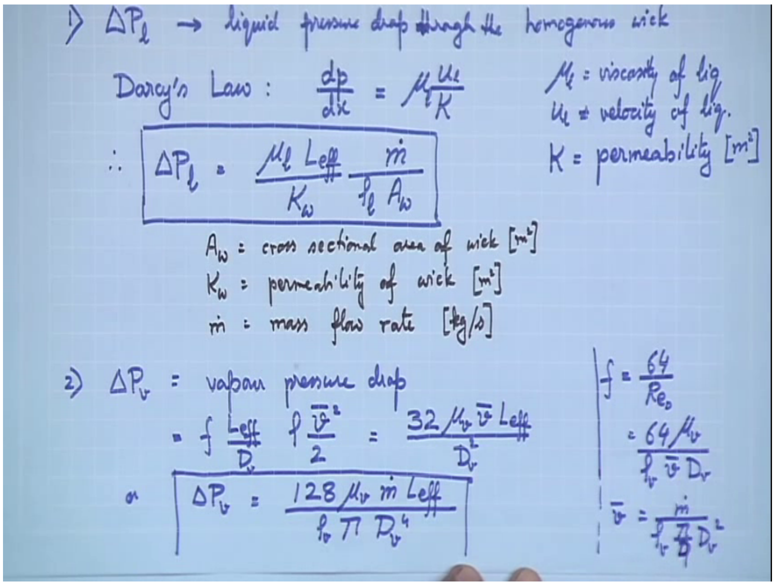

1) $\Delta P_l \rightarrow$ liquid pressure drop through the homogeneous wick

Darcy's Law : $\frac{dp}{dx} = \mu_l \frac{u_l}{K}$

μ_l = viscosity of liq

u_l = velocity of liq.

K = permeability $[m^2]$

$$\therefore \boxed{\Delta P_l = \frac{\mu_l L_{eff}}{K_w} \frac{\dot{m}}{\rho_l A_w}}$$

A_w : cross sectional area of wick $[m^2]$

K_w : permeability of wick $[m^2]$

$\dot{m}$: mass flow rate $[kg/s]$

2) ΔP_v = vapour pressure drop

$$= f \frac{L_{eff}}{D_v} \rho \frac{\bar{v}^2}{2} = \frac{32 \mu_v \bar{v} L_{eff}}{D_v^2}$$

$$\text{or} \quad \Delta P_v = \frac{128 \mu_v \dot{m} L_{eff}}{\rho_v \pi D_v^4}$$

$f = \frac{64}{Re_D}$

$= \frac{64 \mu_v}{\rho_v \bar{v} D_v}$

$\bar{v} = \frac{\dot{m}}{\rho_v \frac{\pi}{4} D_v^2}$

The first one we are going to talk about is what we said delta P l. Now what is this is again liquid pressure drop through the homogeneous wick. Now for this one what we will use is we are going to use Darcy’s Law Henry Darcy is one of the pioneers of flow through porous media again the wick is a porous material. So, we are going to use Darcy’s law which states that the pressure gradient dp dx can be given as mu u over K this is mu l.

Now what does this mean where mu l is of course, a viscosity of liquid, u l is velocity in that direction since we as saying dp dx we have used u velocity of liquid and K this is important is known as permeability and typically it is dimensions is meter squared.

So, this is Darcy’s law. So, if you use it here then we can write it as therefore, delta P of l for our heat pipe can be written as mu l times, L effective because this is delta p we have integrated over that length, divided by the permeability of the wick I am writing it as K w and then what is left is the velocity, which I am going to write it in the form in that in terms of mass flow rate I am going to write it as m dot and why I am writing it as m dot it will become clear later divided by velocity is mass flow rate divided by density times area. So, rho l times A w. So, A w here cross sectional area of the wick again denoted by a meter squared K w permeability of wick also denoted by meter squared and the rest of it is standard definitions we all know that m dot, let us call it mass flow rate given by kg per second. Next is this is number 1 and so we have got this expression little box it 2.

Next 1 we are going to call is delta P v. What is delta P v? So, that is a vapor pressure drop and this one we can write it this is pretty well known to us our standard f L effective by D rho, let us write it as v over here v bar squared by 2 is a standard definition for steady incompressible flow through a pipe right. And this again we can write it as what is f f for flow can be written as 64 over Reynolds number or if we expand Reynolds number 64 viscosity of the vapor divided by density of the vapor times the mean velocity times D, which is the inner diameter of the core right.

So, therefore, let us put this back here and write it as thirty 2 mu v times v bar l effective over let us call it as D v because diameter of the vapor core D v squared or finally, let us box it in this way or delta P v is going to be 128 mu v m dot l effective divided by rho v Pi D v to the power 4 let us box it, why what have you used we have used v bar as m dot over rho v Pi by 4 sorry D v squared .

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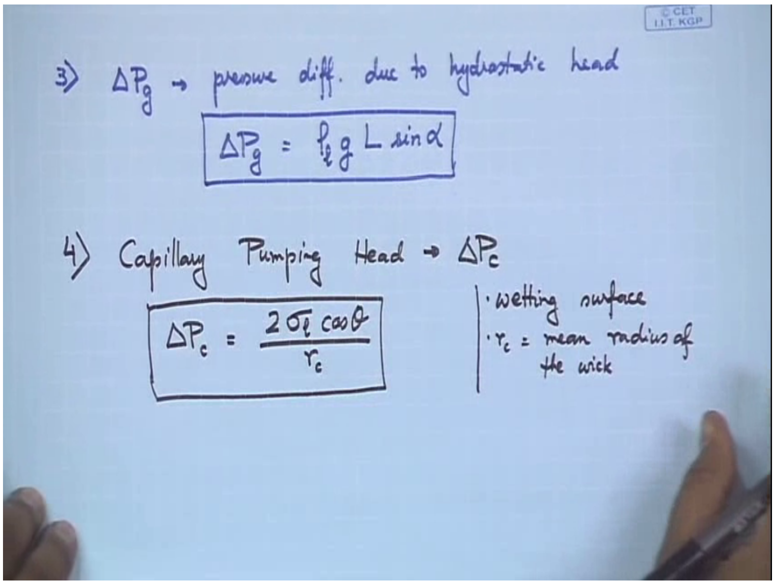

3) ΔP_g → pressure diff. due to hydrostatic head

$$\boxed{\Delta P_g = \rho_l g L \sin\alpha}$$

4) Capillary Pumping Head → ΔP_c

$$\boxed{\Delta P_c = \frac{2\sigma_l \cos\theta}{r_c}}$$

- wetting surface
- r_c = mean radius of the wick

The next one which is number 3 is the gravity force delta P g this is pressure difference due to hydrostatic head, which for our figure can be written to be delta P g is equal to rho g L sin alpha . So, let us put these things over all over again this is what we wanted to have delta P l, delta P v, delta P g and we have expressions for all 3 delta P l, delta P v, delta p g. So, the final thing that is remaining is the left hand side.

What about the capillary pumping head and I am going to use a different thing here Capillary Pumping Head or delta P c so the driving force in the wick is what the driving force in the wick is surface tension right. So, you remember from our high school delta P is 2 sigma over rc right sigma is the surface tension coefficient for a particular bubble of bubble inside water we had done all these derivations. So, I am not going to go into those details. So, what I will right now is just the expression for delta P capillary head. So, what I am going to write is to obtain the capillary driving force I can write it as we are going to use some assumptions I am going to write it as 2 sigma l cos theta rc . So, what I will have be used. So, what I have used is the following.

We have used definitely wetting surface or hydrophilic surface otherwise no point using hydrophobic surface in a wicking material. So, that is obvious rc is the mean effective radius of the wick, that is pretty much it this is all that we have studied of course, we also know that for perfectly wetting surface cos theta equals to one or theta equals to 0. So, wetting angle is 0 perfectly wetted. So, this is we have assumed a wetting surface, but not a perfectly waiting surface yet. So, what are we going to do now we are going to use these 4 expressions that we have derived and put it back into our momentum balance or the pressure balance which we had written as what delta P c max must be greater than or equal to delta P l plus delta P v plus delta P g .

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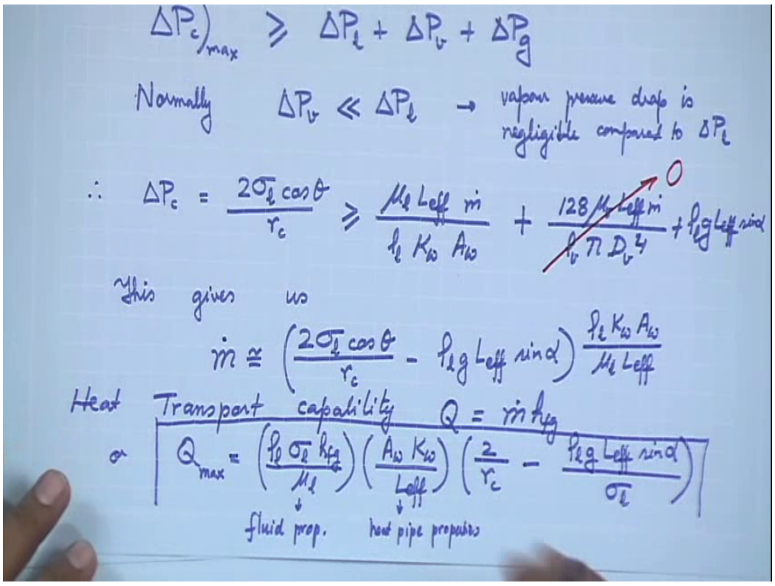

$$\Delta P_c)_{max} \geqslant \Delta P_l + \Delta P_v + \Delta P_g$$

Normally $\Delta P_v \ll \Delta P_l$ → vapour pressure drop is negligible compared to ΔP_l

$$\therefore \; \Delta P_c = \frac{2\sigma_l \cos\theta}{r_c} \geqslant \frac{\mu_l L_{eff}\,\dot{m}}{\rho_l K_w A_w} + \cancelto{0}{\frac{128\,\mu_v L_{eff}\,\dot{m}}{\rho_v \pi D_v^4}} + \rho_l g L_{eff} \sin\alpha$$

This gives us

$$\dot{m} \cong \left(\frac{2\sigma_l \cos\theta}{r_c} - \rho_l g L_{eff} \sin\alpha\right)\frac{\rho_l K_w A_w}{\mu_l L_{eff}}$$

Heat Transport capability $Q = \dot{m} h_{fg}$

or $$\boxed{Q_{max} = \underbrace{\left(\frac{\rho_l \sigma_l h_{fg}}{\mu_l}\right)}_{\text{fluid prop.}} \underbrace{\left(\frac{A_w K_w}{L_{eff}}\right)}_{\text{heat pipe properties}} \left(\frac{2}{r_c} - \frac{\rho_l g L_{eff} \sin\alpha}{\sigma_l}\right)}$$

Now, normally the vapor pressure drop which is delta P v is much less than delta P l, in other words a vapor pressure drop is negligible compared to liquid pressure drop to the wick . So, therefore, what we get is delta P c max, which is 2 sigma l cos theta over rc must be greater than equal to mu L L effective m dot rho l kw aw we all know this is coming from Darcy's law plus. Let me write the thing and then we will strike it to 0 mu v l effective m dot rho v pi D v to the power 4 plus rho l g l effective sin alpha and what we said is this we will said to 0 and let us also said this to equality sign because this is what it has to be greater than equal to. So, at a minimum it should be equal to and what we can write therefore, is this gives us m dot is equal to 2 sigma l cos theta over rc minus rho l g L effective sin alpha times rho l kw aw mu l L effective.

So, therefore, what did we want we wanted to have the heat transport capability which is apr Q is going to be m dot h f g because this is the mass flow rate that is getting vaporized at the evaporator end. So, the therefore, this mass flow rate times the latent heat of vaporization is going to give me the total amount of heat that can be removed and this can be shown to be equal to is equal to let me write it is a very beautiful expression that comes through sigma l hfg over mu l times A w K w over L effective times, 2 over r c let me call it as Q max 2 over rc why because I am talk talking about max and maximum happens when cos theta equals to 0 sorry cos theta equals to 1 and theta or theta equals to 0. So, 2 over rc minus rho l g L effective sin alpha over sigma l.

This is what we set out to come up to derive and this is what we have got. Why did I say this is a nice expression look at this term in the first parentheses, what is it rho l sigma l hfg mu l all of them are fluid properties. So, these are all fluid properties what is the next 1 A w K w over L effective, what are these this is area of the wick this is permeability of the wick this is effective length of the heat pipe right. So, these are the heat pipe properties of wick and geometry and the rest of it is a combination it has both fluid properties as well as geometrical properties we cannot help here much, but think about it over here.

Let us look at this the term alpha when is this maximum when alpha is equals to 0 right no not really why not really if alpha equals to 0 you get something, but what is alpha equals to 0 it means perfectly horizontal remember alpha sin alpha can be negative also. So, this is not essentially a positive quantity. So, if sin alpha becomes negative then actually this term becomes larger and when will it be negative that is when you have it perfectly vertical. So, sin alpha is minus 1 correct. So, when sin alpha is minus 1 which means that the heat pipe is vertical like this with the evaporator below condenser recall over here in this picture that I had drawn, this was condenser below evaporator above you actually have to tilt it you have to tilt it like this and make it vertical and that is when you will get maximum clear.

So, we can recall this is maximum when sin alpha is minus 1 which means the heat pipe is vertical with evaporator below condenser be and why because in that case gravity helps the liquid to come through the week from vertically downwards. So, this kinds of gives us this was a mathematical analysis and gives us the maximum amount of heat transport that can happen inside a heat pipe and again recall this is a good definition definitely .

Another thumb rule is this is for a straight pipe, but many a times you saw some of these some of these figures in a laptop or for deicing there are bends anytime you have a bend the transport capability goes down. So, with bends with narrowing of cross section etcetera the transport capability does go down all right

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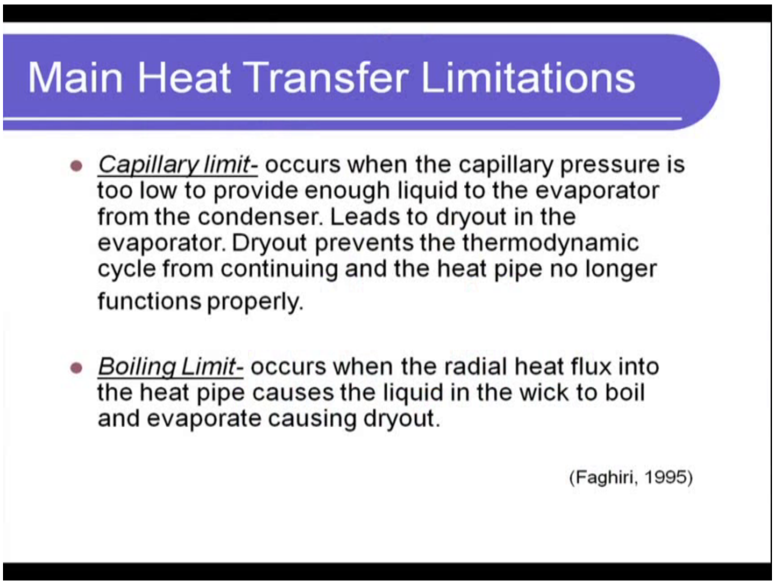

Main Heat Transfer Limitations

- *Capillary limit-* occurs when the capillary pressure is too low to provide enough liquid to the evaporator from the condenser. Leads to dryout in the evaporator. Dryout prevents the thermodynamic cycle from continuing and the heat pipe no longer functions properly.
- *Boiling Limit-* occurs when the radial heat flux into the heat pipe causes the liquid in the wick to boil and evaporate causing dryout.

(Faghiri, 1995)

So, quickly now let us go over to some of the limits. So, this is maximum heat transport capability we have seen that, but what are the limits even here also what are some of the limits that we can face.

So, the first one we are talking about is the capillary limit. So, when the capillary pressure is too low to provide enough liquid to the evaporator from the condenser and that leads to dry out the evaporator. So, which kind of comes from this analysis also if the capillary pumping head is not enough, if the liquid cannot come down from the condenser to the evaporator, but the same time you are supplying heat at the evaporator what will happen the liquid at the evaporator end will vaporize go, but it t would not come back. So, this will lead to dry out. So, dry out means the evaporator section is completely dry you are supplying heat, but there is no liquid that is left to evaporate.

Boiling Limit. So, boiling limit is when the radial heat flux into the heat pipe causes the liquid in the wick to boil much higher or much more completely than then what is allowed and therefore, it leads to dry out and this also comes from this Q max if you supply something which is larger than Q max then what happens? You are boiling the fluid at a higher rate compared to the rate at which you are getting back the liquid. So, as the result what happens as the result you will soon have a place have a have a scenario, but the entire liquid in the evaporator has boiled off because your heat flux is high, but the liquid has not come back this also leads to dry out. So, the same phenomenon dry out in one case happens in the capillary limit happens because a wick does not have enough capillary head and in other case happens because you have suddenly your heat flux has gone up. So, high that the wick is unable to cope up and pump back the liquid. So, you do not have enough liquid left in both cases you do not have enough liquid left to remove the heat or to boil off and exte and extract the heat.

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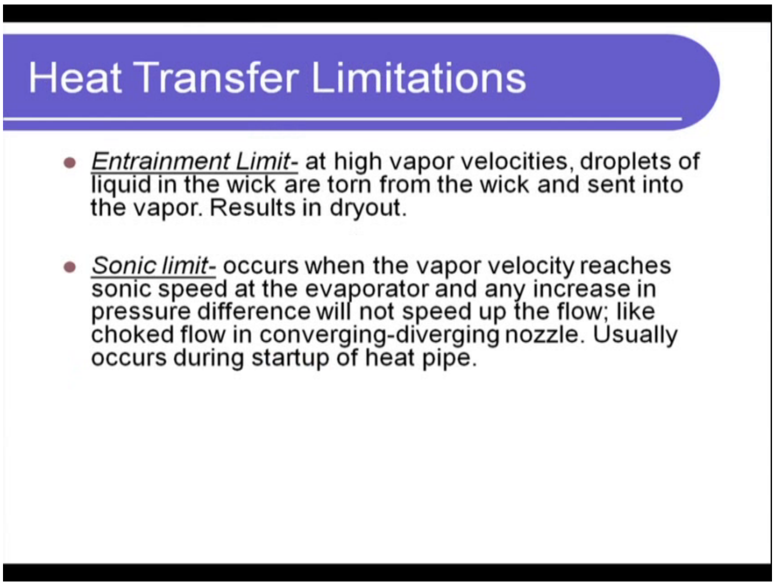

Heat Transfer Limitations

- *Entrainment Limit-* at high vapor velocities, droplets of liquid in the wick are torn from the wick and sent into the vapor. Results in dryout.
- *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; like choked flow in converging-diverging nozzle. Usually occurs during startup of heat pipe.

Entrainment Limit. So, this is interesting this happens at very high flow velocity vapor velocities the vapor velocity through, the core where what happens is because of the friction between the liquid that is flowing through the wick and the vapor that is flowing through the core the force between the 2 at the interface it can so happen that some of the vapor which is flowing will try to drag a few droplet us of liquid from the wick tear them off from the wick and entrain it along the vapor core. So, that is called the entrainment limit.

So, when the vapor velocity is very high that can happen some of the liquid from the wick can get dissociated from the wick and join the you know fast moving vapor as droplet us in truth and flow through the core to the evaporator section sorry to the condenser section. And the last 1 is the sonic limit which also occurs because of the very high vapor velocity because when it reaches sonic limit when it reaches velocities which is similar to that of sound. And so that can lead to choking and a lot of undesirable effects as I shown here it can sometimes happen during startup of the heat pipe so, suddenly if the heat if let us say your heat source is not working let us say in a laptop for example, and then you suddenly switch it on and the CPU is running at running at very high power this may happen, but typically you know when we switch on a computer, it typically switch is on in an idle mode and then you start then you start launching applications and that is when the heat dissipation slowly gradually increases so, but the sonic limit we need to be aware of what it is.

So, that is kind of our discussion on heat pipes.

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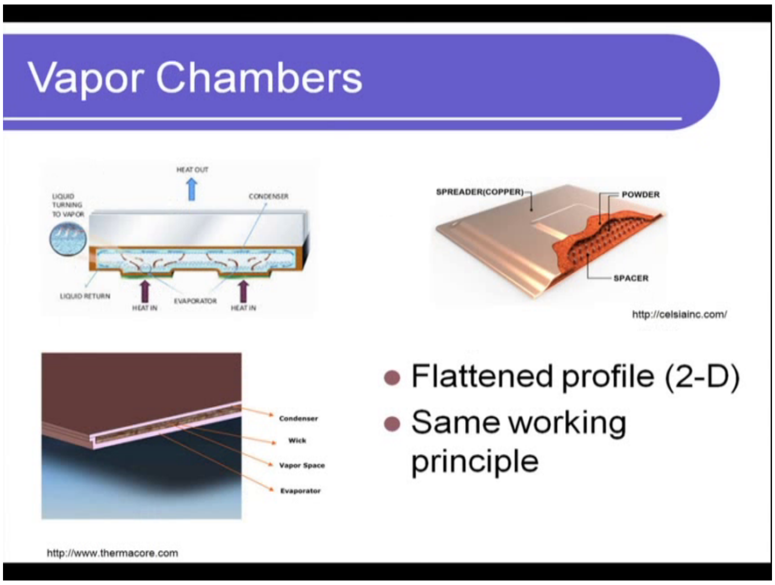

Vapor Chambers

http://celsiainc.com/

- Flattened profile (2-D)
- Same working principle

http://www.thermacore.com

Let us quickly end with a couple of other techniques the first one is called Vapor Chamber. Vapor Chamber the way it happens it is kind of the if the working principle is the same is the same as that of a heat pipe, but it is a 2-D structure. So, as a shown in the schematic a vapor chamber can be a very nice heat spreader for example, where if you have multiple sources of heat here also it is a 2 d hollow case casing and with a wick along the internal wall and what is happening is the entire surface at the top is the condenser.

So, again what happens the heat goes the heat is supplied over here through this heat source the liquid drops boil off goes to the condenser go. So, in this case flows up goes to the condenser it gets cooled down and is brought back through the wicking action. So, essentially it is the same as a heat pipe except that the configuration is different it is a planer 2 d flattened profile with the same working principle where one end of this plate so, it will comes off comes as a plate one end is the heater the other end is a condenser all right.

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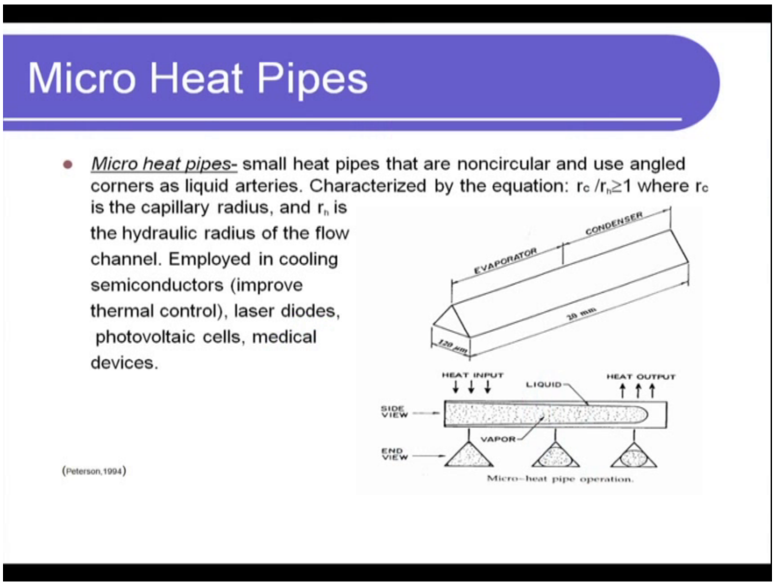

Micro Heat Pipes

- *Micro heat pipes-* small heat pipes that are noncircular and use angled corners as liquid arteries. Characterized by the equation: $r_c / r_h \geq 1$ where r_c is the capillary radius, and r_h is the hydraulic radius of the flow channel. Employed in cooling semiconductors (improve thermal control), laser diodes, photovoltaic cells, medical devices.

Micro–heat pipe operation.

(Peterson,1994)

Micro Heat Pipes is where you do not have a wick it is a wick less structure, where it has short corners and bends and sometimes narrow groups and those themselves provide the capability action, because the radius or the effective radius the capillary radius and the hydraulic radius of the flow channel are comparable. So, this is also used especially if in many of the electronic app small electronic applications it is used not so much for waste heat recovery.

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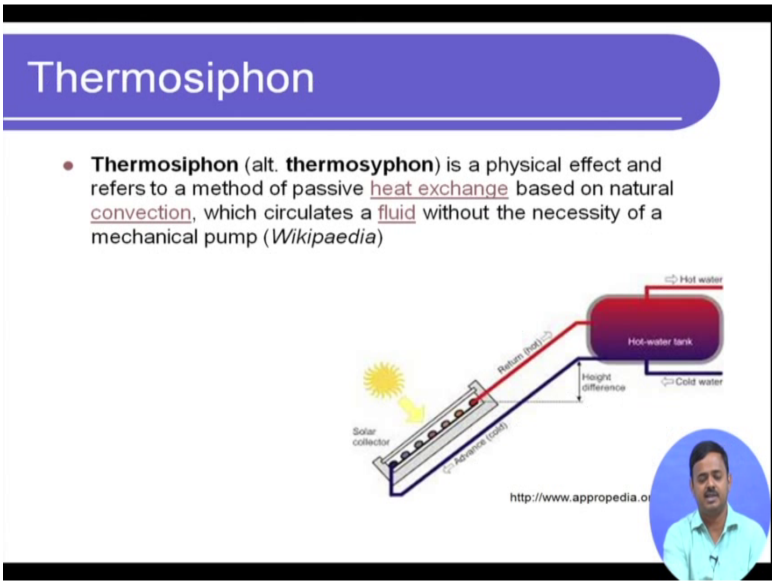

Thermosiphon

- **Thermosiphon** (alt. **thermosyphon**) is a physical effect and refers to a method of passive heat exchange based on natural convection, which circulates a fluid without the necessity of a mechanical pump (*Wikipaedia*)

http://www.appropedia.o

And finally, we should also know something about Thermosiphon, what is the difference between the heat pipe and Thermosiphon. So, Thermosiphon the way it works is it is completely driven by density difference, one of the most common examples that I have seen is our solar heaters or solar water tanks where what happens is the cold water gets heated in the in the solar collector and because it is density is lower sorry because it is density is lower it goes to the tank and from where we can get hot water, and then again the cold water comes back and heated in the loop.

So, the entire flow happens due to density difference; completely natural circulation it is about completely passive there is no wick unlike a heat pipe where the flow back of the liquid cold liquid happens because of capably reaction through the wick and also there is a phase change in a Thermosiphon there may or may not be a phase change, but in case of a heat pipe there has to be a phase change well Thermosiphon source typically also we most of the times is associated with phase change , but again the basic difference is this flow is completely driven by density difference and there is no pumping action due to wick unlike in a heat pipe all right.

So, that kinds of brings us to an end on the topic of heat pipe, again to recap we started by understanding what is the heat pipe, how it looks and how it works. Then we talked about a few application in terms of waste heat recovery, we talked about gas to gas heat recovery, we talked about deicing, we talked about applications in I.C engines and gas turbines and we also talked about application is electronics cooling which is per se not strictly waste heat recovery what is more of a cooling application.

We then went over to study and derive an expression that will help us quantify the maximum amount of heat transport capability of a heat pipe and we saw that it depends on a variety of parameters including fluid properties, as well as geometry of the heat pipe, as well as the wick properties. And then we also talked about some limits that a heat pipe may face we talked about 4 limits; capillary limit, boiling limit, entrainment limit, and sonic limit. And finally, we wrapped up our discussion by looking at vapor chamber which is a 2 D heat pipe you may call it so in a flattened profile and also Thermosiphons which works in many ways is similar, but works due to density difference and does not contain a wick.

So, heat pipe again it is a special heat exchange device, it is a continuation of heat exchanger that we were discussing before, but here we saw heat pipes how it can be used for waste heat recovery. So, in the next class we will move on to another topic till then thank you very much hope you enjoyed this and learnt some new things through this discussion on heat pipes and next class we will learn something new.

Thank you very much.