Heat Exchangers: Fundamentals and Design Analysis
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Lecture - 45
Heat Pipes and Heat Exchangers

Hello participants. So, we are again back we were learning Heat pipes and Heat Pipe Heat exchangers. We will continue with this. So, two lectures we had on heat pipe and heat pipe heat exchangers. And there basically we have seen the fundamentals that means the basic construction of the most primitive heat pipe. Over the years there are different kind of heat pipes which we will see later on. that is one capillary wick supported constant cross section heat pipe which was developed at the beginning and which is still very comprehensively used and most of the heat pipes are of that particular design.

And then their certain applications some important features etcetera we have seen. Today we will move to a important aspect of heat pipe that is we will move to the modelling of heat pipe.

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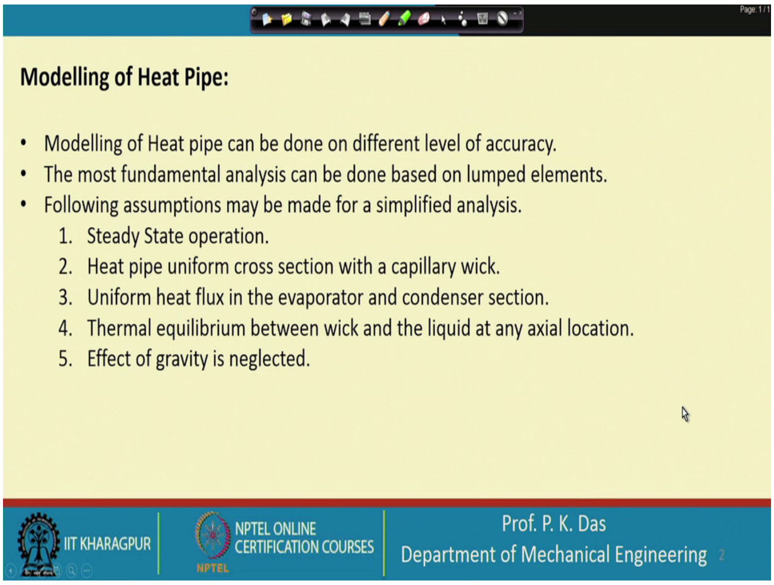

Modelling of Heat Pipe:

- Modelling of Heat pipe can be done on different level of accuracy.
- The most fundamental analysis can be done based on lumped elements.
- Following assumptions may be made for a simplified analysis.
  1. Steady State operation.
  2. Heat pipe uniform cross section with a capillary wick.
  3. Uniform heat flux in the evaporator and condenser section.
  4. Thermal equilibrium between wick and the liquid at any axial location.
  5. Effect of gravity is neglected.

So, let me say or let me a state that the modelling of heat pipe what we are trying to do that is basically the conventional heat pipe or the most primitive and most basic heat pipe that is capillary wick supported heat pipe.

Modelling of heat pipe can be done on different level of accuracy. Even for this particular heat pipe one can do at different level of accuracy. Considering a fully three dimensional model. All the complexities of a fluid flow, heat transfer, phase change etcetera one can take care of; taking into consideration all the geometric details that can be done. That is that may be very elaborate, but that is not impossible.

But at the same time that may be counterproductive because you see industry cannot have so, much of time for designing a heat pipe. So, there could be some sort of simplified model again simplified model could be lumped element model could be one dimensional model could be two dimensional model like that. And we are going into a simplified model.

So, if we look into the PPT then we will see the most fundamental analysis can be done based on lumped element. So, you will do one lumped element kind of analysis. Following assumptions may be made for simplified analysis. Steady state operation actually for design one can do steady state analysis, but the analysis I will show that will give you the procedure for doing transient analysis also. Heat pipe of uniform cross section with a capillary wick that is what I have told that is the basic structure of heat pipe.

Uniform heat flux in the evaporator and condenser section, thermal equilibrium between the wick and the liquid at any axial location that means at any axial location we will assume that the wick structure that is generally the metallic structure most of the cases.

So, that metal and the liquid within the pores of the wick they are at the same temperature. Then effect of gravity is neglected in this analysis effect of gravity is neglected, but one can include the effect of gravity if the person likes. So, let us go to the most simplified analysis of or modelling of heat pipe next slide.

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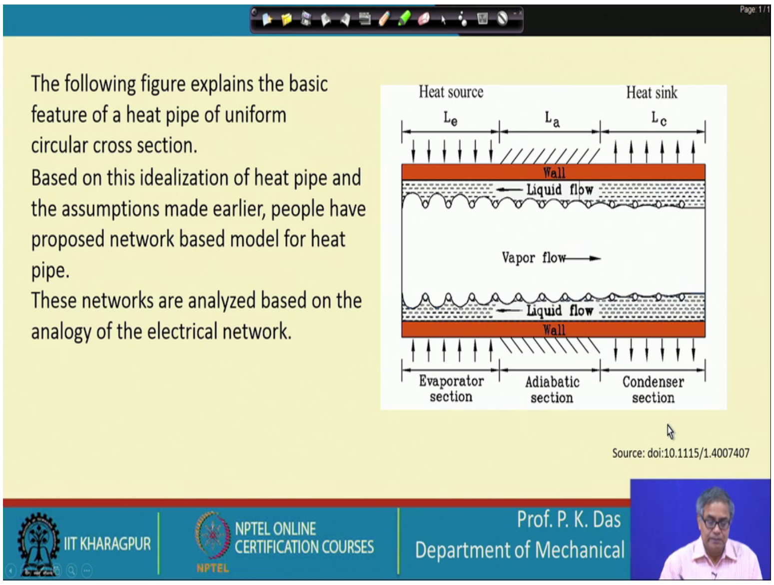

The following figure explains the basic feature of a heat pipe of uniform circular cross section.

Based on this idealization of heat pipe and the assumptions made earlier, people have proposed network based model for heat pipe.

These networks are analyzed based on the analogy of the electrical network.

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So, in the next slide I am showing you one diagram of the heat pipe. You can appreciate by now we have learnt heat pipe. So, this is the container which is a tubular container in most of the cases or wall of the heat pipe which is metallic. And solid wall then close to the very close to the wall and inside this container there will be some sort of a wick. There could be different design of the wick as we have discussed. And this is liquid impregnated or this is liquid saturated wick. That means the pores that will be filled up with liquid.

And then from the outside if we see there are three sections which are very important you know that is the evaporator section where heat is coming inside the heat pipe then there is an adiabatic section. There is in the adiabatic section almost no heat transfer from the heat pipe to the surrounding and then there is a condenser section where heat is rejected by the heat pipe.

So, inside again if we come we will see the vapour will be generated in the evaporated zone. And it will move in the direction towards the condenser so, through the central region.

So, this is the vapour flow area. And in the condenser region the liquid will be condensed and this liquid will be transported by capillary action back to evaporator. And the liquid flow rate is in a direction opposite to the direction of vapour flow.

Another thing I like to see you minutely. You see the liquid meniscus. Here we can see the meniscus are curved and as we move towards the condenser the meniscus are not curved they are more or less flat.

So, in the evaporator section they are curved and towards the condenser section these curve curvature reduces and ultimately they are more or less flat in the condenser section.

So, in the evaporator section basically evaporation takes place and liquid is converted into vapour. So, here we are getting this kind of geometry of the free surface or meniscus. So, that is one aspect of heat that means, liquid evaporation is taking place and that is why we are getting this.

But the another aspect this curvatures are very important because due to the presence of the curvature at the interface there will be a pressure difference. So, this is called capillary pressure and this pressure difference is very important for the operation of the heat pipe. Basically this is the driving force for the liquid circulation for the fluid circulation.

So, what is the fluid circulation vapour is moving in this direction and liquid is moving in the opposite direction in a counter flow to counter flow or counter current kind of manner. And these circulation vapour and liquid flow it has to be supported by some sort of a pumping power and that pumping power is coming from the capillarity of the design.

So, this is very important. So, once we understand this the following the basic feature of heat pipe of uniform cross section and the assumption we have made we can now move forward for analysis.

People have proposed network based model for heat pipe. So, what people have done people have modelled the heat pipe at a very basic levels which is called network.

So, people call it sometimes thermodynamic network of heat pipe. Basically it is a lumped element model there are different nodes or lumps connected by network and basically there will be two network which we will see.

So, these networks are analysed based on analogy with electrical network. So, electrical circuit analysis we are familiar. All engineers are familiar they have done some electrical circuit analysis at some time of their training.

So, with electrical circuit analysis we can do this or with the analogy of electrical circuit analysis we can do the analysis of your heat pipe thermal network or heat pipe thermodynamic network. So, let us move to the next slide.

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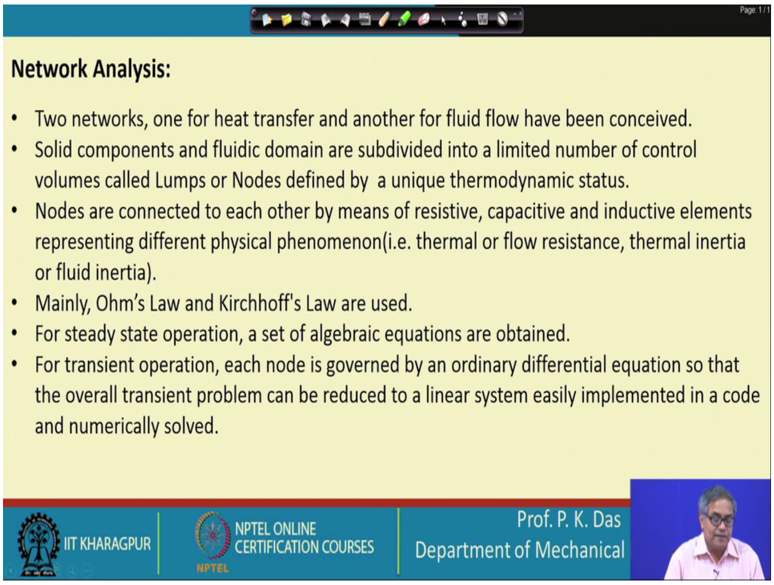

Network Analysis:

- Two networks, one for heat transfer and another for fluid flow have been conceived.
- Solid components and fluidic domain are subdivided into a limited number of control volumes called Lumps or Nodes defined by a unique thermodynamic status.
- Nodes are connected to each other by means of resistive, capacitive and inductive elements representing different physical phenomenon(i.e. thermal or flow resistance, thermal inertia or fluid inertia).
- Mainly, Ohm's Law and Kirchhoff's Law are used.
- For steady state operation, a set of algebraic equations are obtained.
- For transient operation, each node is governed by an ordinary differential equation so that the overall transient problem can be reduced to a linear system easily implemented in a code and numerically solved.

So, network analysis. Two networks one for heat transfer and another for fluid flow has been conceived or perceived. So, two types of network in connection with a heat pipe people can think of or people have thought of.

One is purely for the transport of thermal energy and another for the transport of fluid that means this liquid and vapour. And there should be coupling vane between these two network that means, fluidic network and heat transfer network there should be some sort of a coupling. Then solid components and the fluidic domain are subdivided into limited number of control volumes. Let me explain what is solid component and what is fluidic domain.

Solid component is the wall of the heat pipe that takes part in heat transfer because it is a metal and it should be conducting otherwise the heat pipe will not work. Then adjacent to the metal wall we will have the wick; in the wick there will be some sort of porous again probably most probably metallic structure which is saturated with liquid. So, this lack liquid saturated porous media and the solid wall of the container they contain the solid network. And obviously, energy transfer takes place through this network.

And then there is a fluidic network see the fluidic network the fluid inside the porous medium that is again not stationary that moves from condenser to the evaporator. And then in the core region of the heat pipe there is the vapour which flows from the evaporator to the condenser.

So, these two fluids they constitute your fluidic part of it fluidic domain. And then there are different parts of the heat pipe. What are these different parts? This different parts are at least three parts we have number of times stocked and we can identify.

One is evaporator another is the intermediate adiabatic section and third is the condenser. So, these three parts are there so, one can take them as some sort of separate entity and then we can see that there could be different nodes or different lumps or lumped elements. And if one wants to do a better analysis then each of the component I have or each of the parts each of the portion I have mentioned that is evaporator or condenser they can be subdivided.

So, this is how we get different nodes or lumps. Then nodes are connected to each other by means of resistive, capacitive or inductive elements. Representing different physical phenomenon; that is thermal or flow resistance that is your resistive element, then thermal inertia and fluid inertia etcetera so, these are the capacitive element. So, people I mean people can based on this kind of analogy people can have different element and complete the circuit, complete the network.

Two laws of electrical network analysis are very often used. One is Ohm’s law and another is Kirchhoff’s law. So, these two law are very commonly used for the analysis of such kind of network. For steady state operation a set of algebraic equations are obtained. So, if it is a steady state operation obviously, we will get an algebraic setup equation. For transient operation each node is governed by an ordinary differential equation so, that the overall transient problem can be reduced to a linear system of easily linear system. And easily it can be implemented in a code and it can be numerically solved.

So, basically for steady state the life is simple we will have a set of algebraic equation. And if we want to do transient analysis then each node will give us one ordinary differential equation. You can understand that this will be coupled ordinary differential equation. And then we have to solve them most probably through a numerical method. So, this is what is done in the analysis of your heat pipe through network analysis method.

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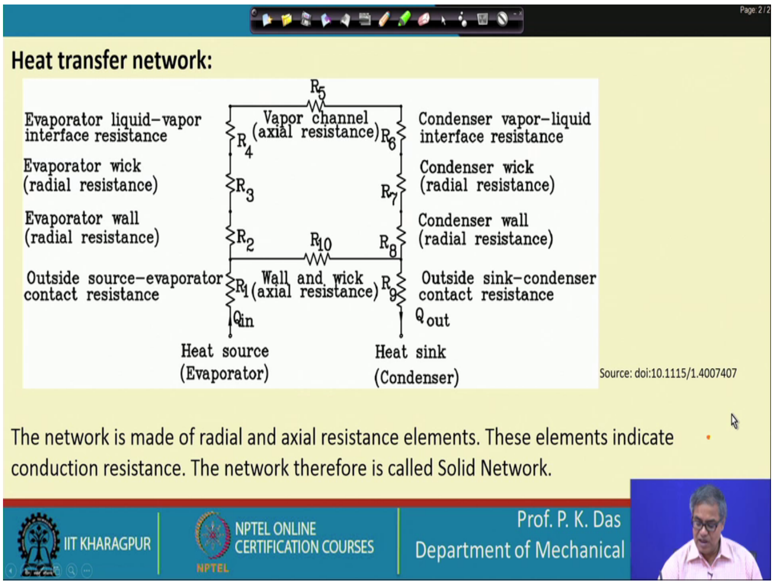

Heat transfer network:

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The network is made of radial and axial resistance elements. These elements indicate conduction resistance. The network therefore is called Solid Network.

Here I have shown a very simplified one can have much more complex, but very simplified network representing a heat pipe. So, if I side by side if draw it will be clear I believe. Side by side let me draw so, that I can make some sort of impression. So, let us say this is my heat pipe. So, here is evaporator section heat is given here, here it is condenser section and this is your adiabatic section. So, these three sections are there.

And obviously, there is liquid flow and vapour flow. So, in between this is your solid wall and this is your porous wall sorry porous wick structure.

So, with this if we try to see so, here you see it heat source or evaporator. Basically I am at this point and then there will be some sort of a resistance and then the heat will enter into the heat pipe. So, there will be some sort of a resistance ok. So, this resistance is shown here and then this side we have got heat sink that is your condenser side here heat is being rejected Q out.

So, this is your Q in and this is your Q out if I like to write so, I can write excuse me sorry we have to go back to the previous slide it is not taking the pen ok.

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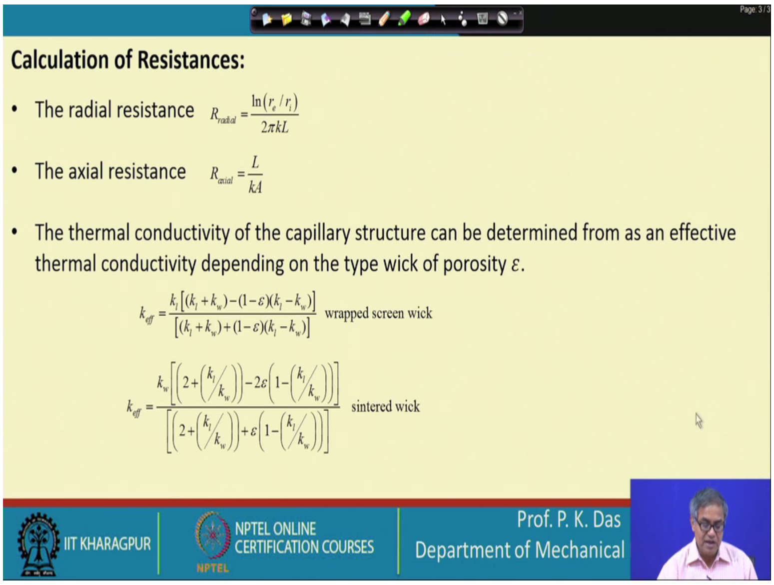

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Calculation of Resistances:

- The radial resistance $R_{radial} = \frac{\ln(r_e / r_i)}{2\pi kL}$
- The axial resistance $R_{axial} = \frac{L}{kA}$
- The thermal conductivity of the capillary structure can be determined from as an effective thermal conductivity depending on the type wick of porosity ε.

$$k_{eff} = \frac{k_l\left[(k_l + k_w) - (1-\varepsilon)(k_l - k_w)\right]}{\left[(k_l + k_w) + (1-\varepsilon)(k_l - k_w)\right]} \text{ wrapped screen wick}$$

$$k_{eff} = \frac{k_w\left[\left(2 + \left(k_l/k_w\right)\right) - 2\varepsilon\left(1 - \left(k_l/k_w\right)\right)\right]}{\left[\left(2 + \left(k_l/k_w\right)\right) + \varepsilon\left(1 - \left(k_l/k_w\right)\right)\right]} \text{ sintered wick}$$

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So, this is your Q in and this is your Q out ok. So, Q in Q out and then from for Q in and Q out we can see that there are two parts. So, either the heat is flowing from this path. So, that outside heat is taking one path and again going back to the environment surroundings or it can take this path.

So, this path R 10; R 10 is the wall and wick axial resistance. So, as I can tell you this resistance elements sometimes they are axial resistance and sometimes they are we have to take the radial resistance.

So, one path obviously, if heat enters over here this is a metallic body. So, some part of the heat will directly go from the some part of the heat will directly go from the evaporator to the condenser through the metallic structure of the wall and of the wick. So, that is what has been shown by R 10.

And then there is an elaborate path. So, this elaborate path how the heat is moving evaporator wall. So, from the evaporator wall heat is moving in the radial direction now then evaporator wick. So, this heat has gone to evaporator wick that is also in the radial direction. Then it has gone to the evaporator liquid vapour interface. So, again it is in the radial direction and then through the vapour channel through the vapour. So, there will be some sort of axial conduction.

So, the heat that is going from here and it is coming to the condenser vapour liquid interface resistance. Then there is condenser wick material interface resistance condenser wall resistance. Now it has reached the condenser and then it will go to the surrounding through this extra resistance which is outside the wall or just adjacent to the wall between the wall and the surrounding.

So, we can see that there are two path one through the metallic structure directly from the evaporator to the condenser. Another is more or less through the radial path of course, there will be vapour channel.

So, more or less most of the resistances are the radial resistance through this resistances heat will come to the condenser section. So, that is what we will get the network is made of radial and axial resistance elements these elements indicate conduction resistances resistance the network is therefore, called solid network.

So, this is what we get for the thermal network. Let me say tell you so, there are many other thermal network taking into account different size. So, suppose I have taken or we have shown there is only one resistance from the evaporator to the condenser through the wall and the wick, but one can have three different resistances one in the all in series one in the evaporator one in the adiabatic section of the tube and another in the condenser.

So, depending on how much accuracy you need. So, you will have different kind of network model. So, let us move to the next slide calculation of resistance. So, we can see that our network model we have different kind of resistances. So, we can calculate the resistances the radial resistance is given by this very well known for a circular tube this kind of resistance comes. So, here there is r e r i. So, outer radius inner radius the conductivity length of the element etcetera or there could be axial resistance. So, this is the cross sectional area A length and k is the conductivity.

Now, the conductivity of the metallic wall we can get, but when we are considering the conductivity of the wick structure. So, these has got so, wick structure is how does the wick structure look? So, the wick structure look like this. So, wick structure look like this let us say this spheres are metallic one and in between we will have pores. So which will be filled by liquid working fluid so.

So, you see it is a composite material both liquid and solid. So, if it is that then we have to have some sort of effective conductivity. Now effective conductivity we can have by this formula two formulae have been shown. The thermal conductivity of the capillary structure can be determined. So, in case of wrapped screen wick we will have this kind of a formula where k l is the liquid conductivity k w is the solid conductivity and epsilon is the porosity.

So, similarly for sintered wick we will get another formula. So, this is how we will get the conductivity.

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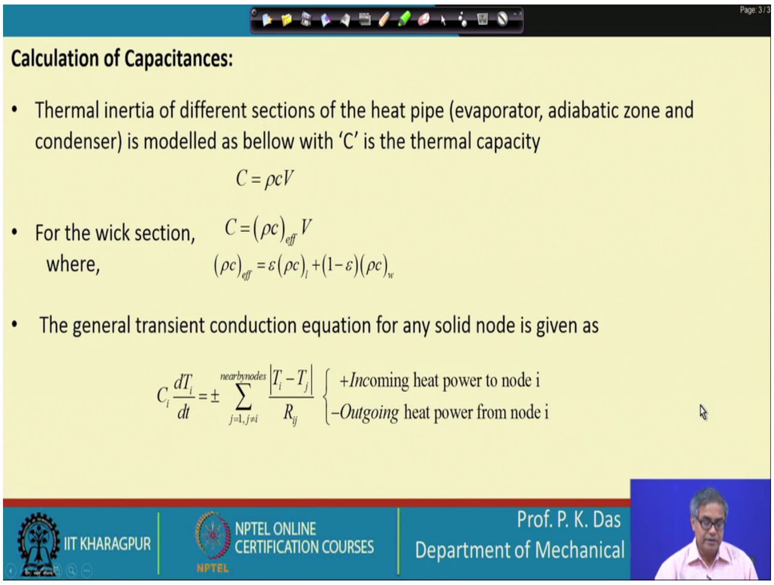

Calculation of Capacitances:

- Thermal inertia of different sections of the heat pipe (evaporator, adiabatic zone and condenser) is modelled as bellow with ‘C’ is the thermal capacity

$$C = \rho c V$$

- For the wick section, $C = (\rho c)_{eff} V$
  where, $(\rho c)_{eff} = \varepsilon (\rho c)_l + (1-\varepsilon)(\rho c)_w$

- The general transient conduction equation for any solid node is given as

$$C_i \frac{dT_i}{dt} = \pm \sum_{j=1, j\neq i}^{nearbynodes} \frac{|T_i - T_j|}{R_{ij}} \begin{cases} +Incoming \text{ heat power to node i} \\ -Outgoing \text{ heat power from node i} \end{cases}$$

Now if we move to the next slide how can we calculate the capacitance because each of the lump or each of the node they will have some capacitance. And if we consider the transient problem then the consideration of capacitance is very important. So, basically we are talking about thermal inertia and thermal capacity. So, this C is the thermal capacity and it is given by rho C into V. Rho is the density C is the specific heat and V is the volume.

For the wick section of course, the rho and C both has to be taken effective density and effective specific heat. So, here we have shown how it can be calculated. The rho C effective how it can be calculated knowing the porosity of the material. The general transient conduction equation for any solid node is given by this particular formula. This is the capacitance this is the temperature.

Actually let me tell you that each of the node will be denoted by a particular temperature. Because it is the lumped element each of the node is a lumped element. So, each of the node will be denoted by a particular temperature. And how the temperature is changing with time that is what we want to look into in case of our transient modelling.

And this is you see that how one can set up an equation this is the thermal capacitance this is the temperature of the node small t is the time this is the resistance between the resistance of the element between two nodes i and j and again T i T j are the temperature.

So, this equation you can see it has got lot of similarity with electrical network. And we can have a setup equation like this. So, with this we can proceed we will have a large number of equation and then we can proceed for our calculation. So, let us go to the next slide

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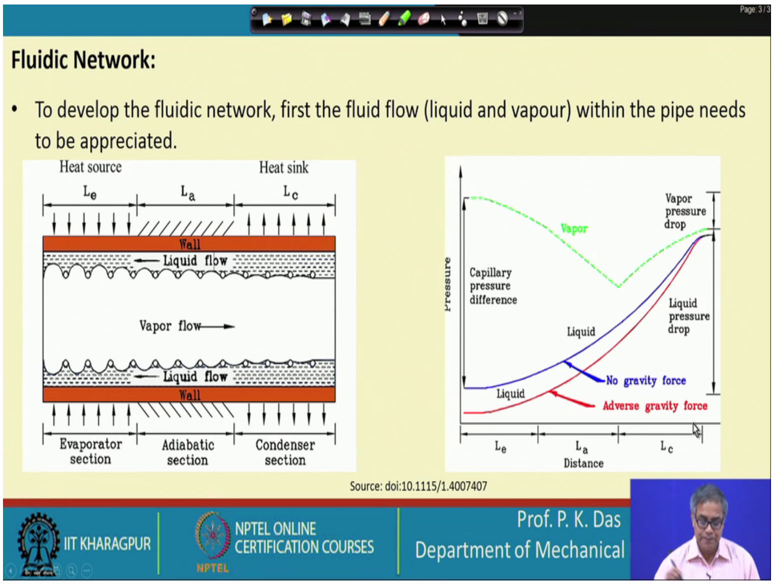

Fluidic Network:

- To develop the fluidic network, first the fluid flow (liquid and vapour) within the pipe needs to be appreciated.

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Next slide shows us the fluidic network. So, here again what we will do we will consider how the fluid flow takes place in connection with the heat pipe. I am showing on the left side and the characteristics of the fluid flow is on the right hand side and that is what we will try to consider and we will try to develop a fluidic network. First the fluid flow has to be understood and then the network has to be developed.

So, what I will this will take little bit of time. So, we will do it in the next class just now I have introduced what we have just I have introduced that what we need to do now. So, I like to end this lecture over here. Next lecture we will take the reference of these two diagrams and again we will start from this point so.

Thank you; thank you for your attention.