Fundamental of Electric Vehicles
Technology and Economics
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Lecture 39
Thermal Design – Part 3

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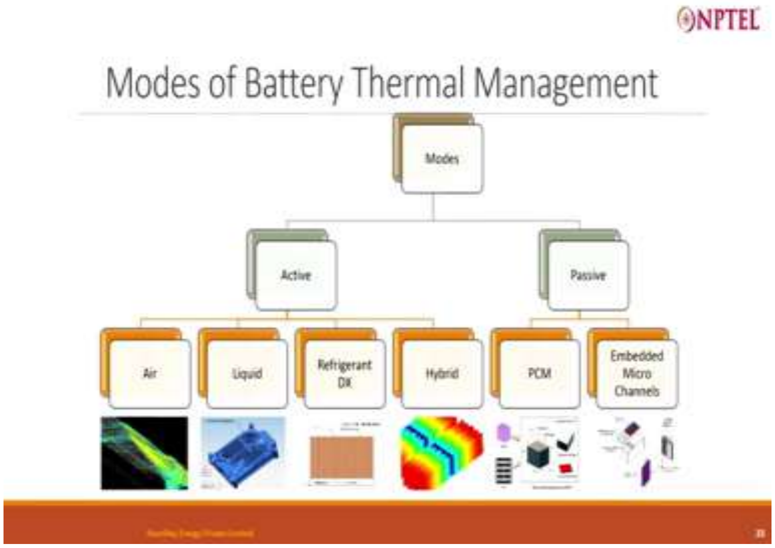

Now will move to the next what are the modes of battery thermal management; so will define every mode here and then we move further. So mode, what are two (modes) so basically there are two modes; one is active and another one is passive. Active is as soon as there is a change in temperature; so there is a means is available there, there are equipments available there. There is process available there that will try to take over that heat and throw away to them in that is what is active.

Passive is you do not explain and this active require energy, immediately it require energy. In passive, you do not required immediate energy to take out the heat or bring back the heat; that is the basically main difference between active and passive. However, to charge or discharge the passive thermal management, you need energy. But, that could be outside whenever it is cheap, or you can utilize the environmental factor; all those things is possible with the passive.

Now, in active thermal management what are the things comes? The air cooling system one of them is air cooling system. So, now since I have to maintain the temperature between 25 to 35. If my ambient condition is 45, how air will cool the my battery? If I simply take air from the ambient and throw inside the battery pack basically it will increase the temperature, instead of decreasing the temperature, am I right?

So, what we have to do? We have to cool the air, we have to cool the air to a defined limit so that it can cool the battery or it should able to take the heat generated by the battery pack. How can we cool the air? Because now outside temperature is 45, can we put some ice it or can we put something known as refrigeration system there. But, to run the refrigeration system you need the energy.

From where that energy will come? That energy will come from the same energy battery pack. So, with the refrigeration unit, you cool the air and that air you… and the heat is rejected to the ambient, you send that air to the battery pack and it is cool. Now, it is you are wish you want to throw that air simply outside or you want to re-circulate. So, when you are re-circulating that air that means again you are cooling that means whatever heat has be… it has absorbed in the battery pack that air taking from that air, throwing it outside and then again cool air you are sending to battery pack.

What would be the case if the temperature is 10 degree or 0 degree or minus 10 degree? What you have to do at that time? You have to basically heat the air. For heating what you require? Again you require energy from the battery. Now, you are heating, now heated air is going inside, it is heating up the battery pack to your level 15 to 35 or whatever desired temperature is required.

And then now when air is heating the battery pack, it is getting cooled; now it is coming back to your active system. It gets heated up and then again it gets re-circulated. So, what you are doing? You are taking the cold energy and you are throwing outside in the cold environment; so this is how the air cooling system works.

Now, there is another liquid cooling system; liquid cooling system could be water, water glycol mixture or some other material. So again you have to cool in the similar way what we have done for air. However, the volume required for the liquid is much-much lower than; liquid flow is much-much lower than what would have been for air flow.

So, let suppose if my battery pack is small or my C rate is very small, 0.2C, 0.3C, 0.4C, 0.5C something like that. I may prefer to go for air cooling because in liquid cooling I will have one more system there like a chiller or a water heater, other than my refrigeration system. However, when C-rate is very high 1C or 1.5C or 2C it is a preferable mode of thermal management system.

Again let us go back to the last slide, what we have discussed thermal resistance or heat transfer. Heat transfer depends upon whenever I am talking air and liquid, it is basically convective heat transfer. So, what is the delta… one term is delta T, the cross-sectional area remains same, or surface area you say it is a surface area through which it is flowing. H; heat transfer coefficient, convective heat transfer coefficient.

For air, when we are doing force cooling, the heat transfer coefficient is between something like 20 watt per meter per Kelvin to 100 watt per meter square per Kelvin. For liquid, if I am using water or water glycol, it can go to 300, 500, 700; and that is how the volume required becomes very less. However, air is available in the environment liquid either water or water glycol or any such liquid is not easily available. You cannot tap it, so you have to store it on the vehicle or in a battery pack, so that will add weight.

But however a small weight (compare) if I have to, if air would also not have been available in the environment then I have would have taken, if I would have compressed and kept it, the weight would have been much more than the liquid in the liquid cooling system. This liquid could be anything, only the primary requirement of this liquid is, it should not corrode. It should have high heat transfer; it should be cheap available, not poisonous, similar way for air.

Now, there is third there is a third option, I will not take liquid so I will not take air; can we cool it directly through the refrigerant? Yes, we can do. If you have further energy requirement in the sense higher C-rate; 2, 2.5C, 3C I want quickly heat to be remove. What a refrigeration direct expansion refrigeration system does? It gets its changing its phase.

Because of change of phase, the high amount of heat can be extracted. So here we are using phase change, active phase change. And we are also eliminating one another sub-system in either air cooling system we wanted to have something like blower which we are eliminating. In liquid cooling system, we need to have chiller and a pump that we are eliminating.

However, since this its a phase change, it converts from liquid to gas, gas to liquid. There is all and it is pressurized system, the pressure can go for 20 bar, 30 bar, 35 ba; so there is always a chance of leakage. If we can maintain that leakage that there is no leakage; this is one of the best system. Ideally, the fourth one hybrid system, what we are talking about is used everywhere; it is a combination of direct expansion or liquid system, combination of refrigerant or air system, or combination of all the three.

Because it is not only battery, so it is there is power electronics and then there is motor and all those things need to be cool. So it is a combination of these is used in hybrid system and it is most commonly used active thermal management system. Now passive, passive we use again phase change material, phase changing material is what? We are also using here a phase change material, refrigerant is nothing but a phase change material.

But, the density, energy density is very-very high. However, in the simple phase change material, we may not have that much high energy density. However, it is still better than in many of the cases, it may be better than cooling with the ambient air. How does it work? It has a certain melting point or range of melting point, very small range like 35 degree.

So, that means it will start melting from 32 to 36 degree and at that time because of the melting it can take high amount of heat. Only problem with this is one is leakage, it can also leak because now it is changing between solid to liquid. Here it was liquid to gas, so similar way here it was solid to liquid. One problem is the expansion, when phase change happens it expands so that creates extra pressure on the packing because of that leakage can happen that is one.

The second thing is thermal conductivities are very low. To enhance the thermal conductivity we try to fit in metal box or some metallic porous media things and then we pour the PCM there. Third thing is the melting temperature; I cannot use a melting temperature of 25 degree C which would have been best at the temperature of 45 ambient.

Because it will take heat from outside, gets melted and loose its function. However, if ambient is 45 and we use a PCM of 45 degree C; it will still help the temperature not go beyond 45 degree. And every reduction in temperature towards the 15 to 35 degree C helps in improving the life. The another thing is embedded by micro channels; in the micro channels like heat pipes. It does not consume the energy actively.

However it is still able to transfer the heat from inside to outside. Sometimes it can maintain the lower temperature also, by evaporative cooling inside the battery box. So, this is basically various modes of thermal management defined into two active and thermal, sorry active and passive and in that active we have air cooling system, liquid air type thermal management system, liquid type thermal management system, direct expansion or refrigerant and then hybrid; and in passive mostly it is a PCM and embedded micro channel.

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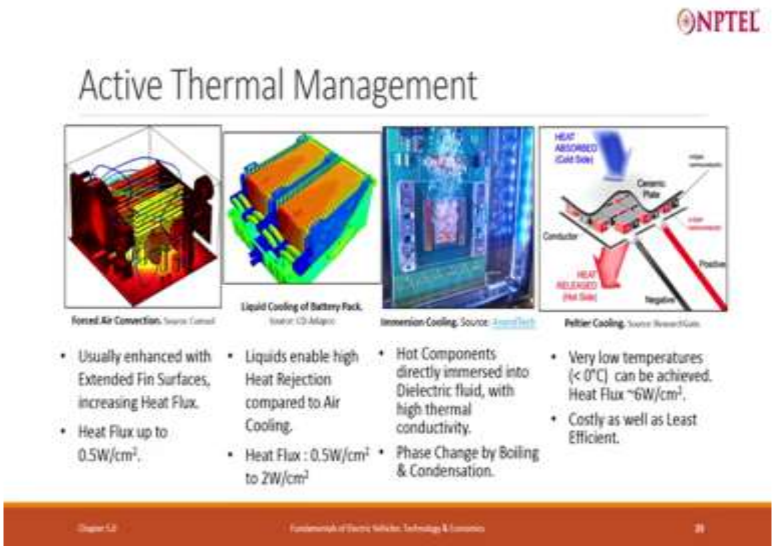

Now, I will show you example of active thermal management system. The first one is forced air convection. You see you have a refrigeration unit, then you have you have refrigeration unit, then you have a blower and that air sent over battery pack. Now, you can further increase a heat transfer by extending the fin surfaces, increasing the heat flux; and we use this heat flux up to 0.5 watt per cm square.

Heat flux is nothing but Q by A, heat transfer you multiply sorry divide by surface area that becomes heat flux. Liquid cooling of battery pack: it enables a high heat rejection compare to air cooling. Heat flux can go up to 0.5 watt per centimeter square to 2 watt per centimeter square. Immersion cooling: immersion cooling is nothing but we dip whole battery pack in a reservoir, in a liquid reservoir.

The benefit of this is you have very nice temperature uniformity. Whatever heat is coming, it is taken by fluid or liquid which can penetrate when a small area available. However, again we have to cool this liquid outside somewhere. This is very popular in high energy or high performing (())(15:09) microprocessor; because the heat flux is very high there. And can be taken only by this method, no other method works out properly.

So, this can again be used in other cases also, however my C-rate should be very high; 5C, 8C, 10C. But, this is a addition of bit, so that also we have to be careful.

Student: What is that liquid?

Professor: Liquid could be anything depends upon temperature, what temperature you wanted to maintain. If you want to maintain let suppose minus 10 degree, so in that case you would go for refrigerant like R134A something like that. If you want to maintain 35 degree or 40 degree, so there artificial material artificial liquid which will start boiling at 35 degree, so that means it is taking heat.

Now, if you have option of (100) to go 100 degree C, best material would be water. Depending upon the temperature end like for an electronic; 70, 75 degree, 80 degree C is good enough. So, material which can boil at 70 degree, 80 degree C is being used.

Student: Whether that material re-circulate it?

Professor: Then that material you have to pump outside, cool it and again resend back or you can also wait that might functionalities only for 30 minutes. So, I am having that much of liquid, 30 minutes all the liquid will start boiling means that much energy. And then after that it would be not use for next 4 hours; so you put extended fin, so it will slowly cool down.

The next one is Peltier cooling, where we are cooling one thing by another effect known as Peltier effect. Peltier effect when you flow the current one surface would become heated, another surface will become cooled. So, if you are if you are cooling it, then the cooled surface would be attached to the surface where you are cooling.

The benefit of this is, you just reverse the polarity. At lower temperature it will start heating up that further, so it can work in both way. However, the performance of Peltier instrument, efficiency I say is very-very low. In heating mode, it gives efficiency we say coefficient of performance more than one. However, in cooling mode as soon as your delta T increases, more than 5 degree, 7 degree; a performance come down to 0.2 COP; coefficient of performance comes down to 0.2, 0.3 like that.

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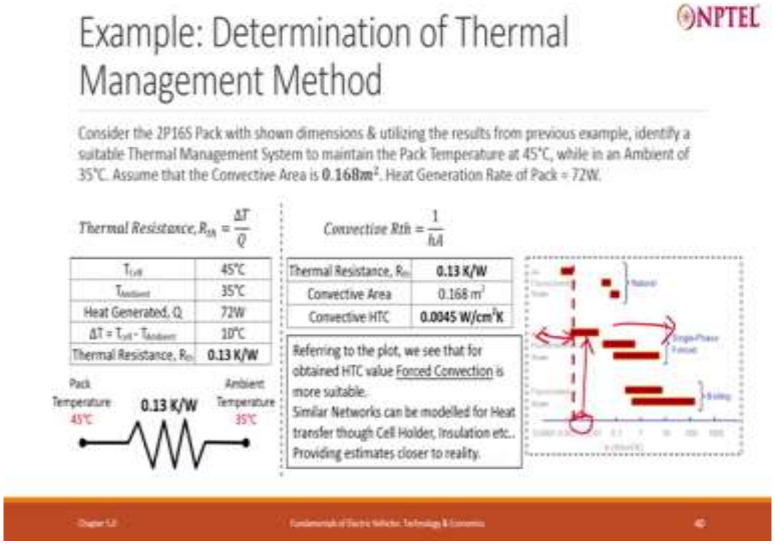

So, how to determine which thermal management system we should use? So there is nice example here; again the same path we have used 2P16S which we have developed. So, consider the 2P16S pack with shown dimensions and utilizing the results from previous examples. The example which we have just talked about what is thermal impedance or thermal resistance and then what would be the heat loss or heat generated.

Identify a suitable thermal management system to maintain the pack temperature at 45 degree C. So, I wanted to maintain the pack temperature at 45 degree C while in an ambient of 35 degree C, my ambient is 35 degree C. Assume the convective area is 0.168 meter square. So what we have seen in the last example, the heat generation rate of the pack is 72 watt, means 72 joule per second.

Thermal resistance is nothing but delta T by Q, actually Q equals to delta T by R. So, what we have put here? R is delta T by Q. So, T cell 45 degree, T ambient is 35, heat generated Q is 72 watt, delta T, T Cell minus T ambient is 10 degree C so thermal resistance you calculate it becomes 0.13 Kelvin per watt sorry K per watt. Now, your temperature is 45 degree, ambient is 35 now you have a resistance in between that.

So, convective resistance is nothing but 1 by hA, so thermal resistance is this one, so convective area is 0.168, convective heat transfer coefficient; what is required is 0.0045 watt per centimeter square Kelvin. Now, there is nice plot here, once you have found out what is heat transfer coefficient; you require it is a convective heat transfer coefficient.

Then you can think of what mode of thermal management system you want to go. So, logarithmic scales here are the bottom, heat transfer coefficient, convective heat transfer coefficient. It can be utilized for other conductive as well as radiative also; 0.0001 to 1000 watt per centimeter square per Kelvin. What we have got here? 0.0045; where it comes? It comes something here.

So, either we can go for natural that means we just provide sufficient channels the air to be flow. So, that would be natural convection, it can dissipate the heat outside or generally packs are sealed properly. I will come back why we seal the packs. In that case if I provide the air channels, I have to force the air or if you keep it open completely in an environment of 35 degree, it can dissipate.

So, that is why we are saying is that the force convection would be more suitable here. So, in that we can maintain the sealing also as well as the heat transfer coefficient also, considering the whole pack. This graph would change slightly application to application; this is just like a thumb rule or basic points where to start. The simplest way of where to start, what should be require this comes something here. What is that? These all three together single phase 4^{th} convection.

In this case of air, it can go fluorochemicals like what we are using generally in Immersion cooling. The Fluorochemical can have a boiling point at different, but heat transfer is generally low. Water or water glycol mixture, so if you see this plot what we see here this comes here in this range. Now, you go up this touches this for air and what is this; fourth convection. Similar network can be modeled for heat transfer though cell, cell holders, insulation.

What we have considered here is only the pack we are not considered anything else. There are other things like you have seen what we have done during the mechanical design; we provide the cell holder for end plate or piped strip. These all are resistance, all are converted into resistance and then you consider that would be either in series or parallel depending upon the path. And then select a suitable method; methodology.

It should be natural convection or force convection or in force convection it is air forced convection, as using the medium air or using the medium water or using the medium water glycol. Any question? This graph is very important graph. This is experimental graph, experimental correlated graph. So, this gives us very nice tool to determine what type of thermal management system I should go, without doing much calculation.

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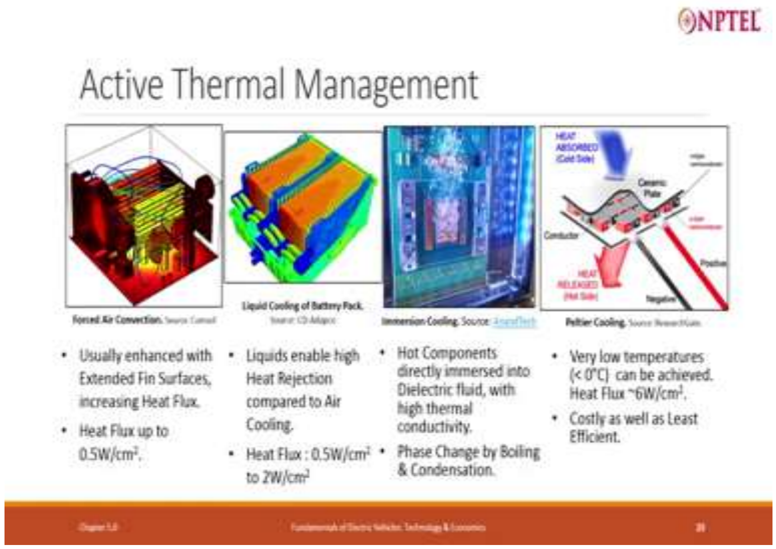

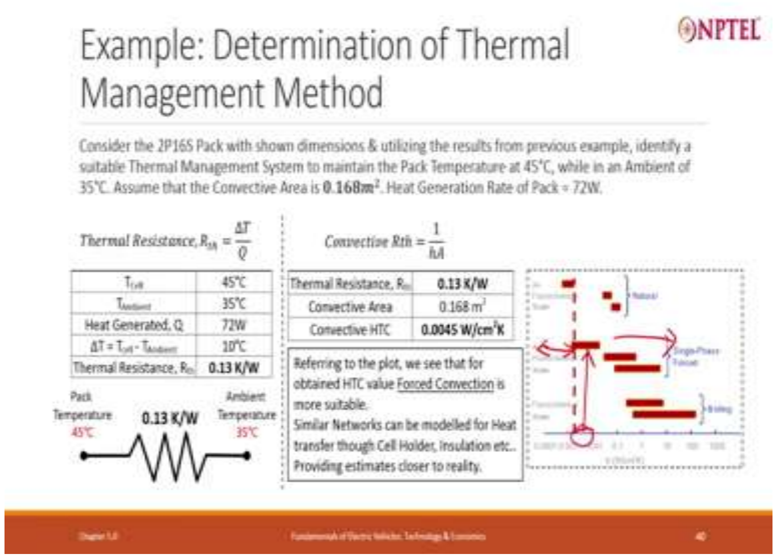

Let us move to next slide; how to make thermal network exactly. This is one number I provided here, this is like a range here I have provided here.

Student: So you have got 0.00045?

Professor: Correct. Its form here if you see here this is coming in from 0.001 up to 0.01 there I have put here it is range, it can go to that range.

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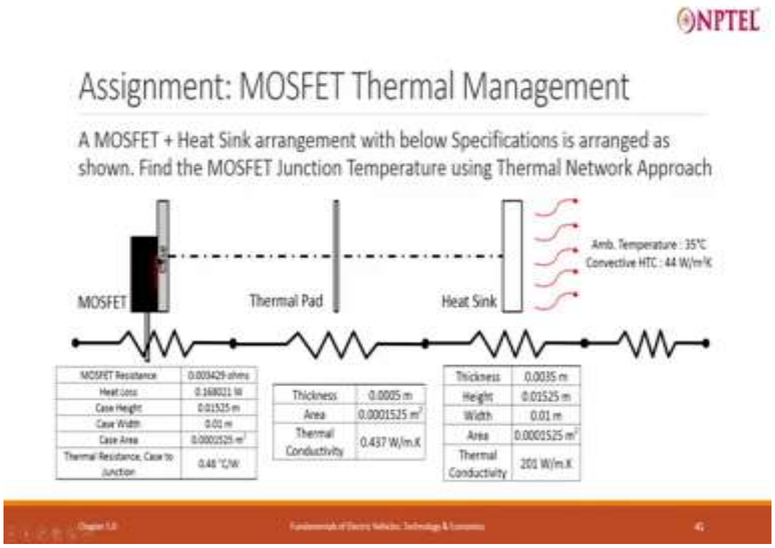

So, now one assignment problem for thermal network. A MOSFET plus heat sink arrangement with below specifications is arranged as shown. Find the MOSFET junction temperature using thermal network approach. What are the things there? MOSFET is there, then there would be generally thermal pad, and then there would be heat sink. And then there is convection to the outside ambient condition; so there is one resistance thermal resistance because of the MOSFET, internal structure itself.

Another thermal resistance will come because of the thermal pad, one more resistance will come because of the heat sink and then at the end the convective resistance. All the parameter for MOSFET is given here thickness, area, thermal conductivity is also given here. For thermal pad, for heat sink, convective heat transfer is also given here, so please find out MOSFET junction temperature; junction temperature is this red, this red here that is junction temperature.

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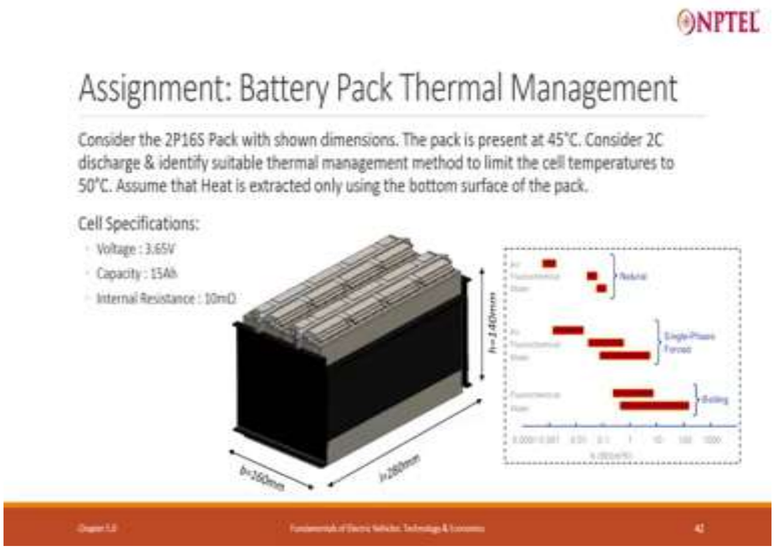

So, another assignment that was on electronics part of the battery pack. Now, we have done 2P16S, so one example problem. Now, the pack is present at 45 degree C, consider 2C discharge; what we have considered there is 1C discharge. Now, let us consider 2C discharge and identify suitable thermal management method out of this; natural, single-phase force or boiling; with water, fluorochemical or water fluorochemical air. What is the constraint? The limit the cell temperature to 50 degree C; we do not want cell temperature to go beyond 50 degree C.

Assume that heat is extracted only using the bottom surface only the bottom surface of the pack. You have all the information for this pack. In the last example problem itself we have done voltage capacity, internal resistance; we have already given you dimensions also here. Let us find out what are the suitable thermal management method is for this particular pack if we have to maintain that temperature at 50 degree C in an ambient condition of 45.

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Passive thermal management system we are talking about. We have already talked about active thermal management system. The passive thermal management system, you do not invest energy at that moment. Most of the time it can be done naturally or like in the case of phase change material. You take it, cool it and then come back; at that place you put energy charge and discharge cycle but not, you are not taking energy from battery.

The simplest example is the heat sink; especially in electronic component mostly we use this passive thermal management system using the heat sink. What we do here? We try to increase the surface area of heat transfer. How can you increase the heat transfer? Q is what; hA delta T, either you can increase h, you can increase A or you can increase delta T to increase Q, or you can do all three. So, what we are doing here we are increasing the surface area of heat transfer; we are increasing A here.

However, up to 0.05 watt per centimeter square that is the maximum we can go with this. Easiest and cheapest to implement and maintain. The same thing we can also do in the battery pack over the cell; you will see a lot of battery pack with a film expose to the ambient. However, the C-rate of those packs will be generally limited to very low. Heat pipes in closed environment when my environment is enclosed; I may not be able to use the heat sink because it needs to be expose to the outside environment.

Is there a way, where I can take heat and put it in to the open environment? The heat pipe is one of the example it takes heat from inside and throw it outside. Again it could be force cooling as well as natural cooling. When it is natural cooling it is generally comes it to the passive thermal management system. Area of the MOSFET generally we consider there.

Student: Not the heat sink

Professor: Not the heat sink because by heat sink we try to increase surface area. So, there was a question here that 0.05 watt per centimeter square heat flux is of MOSFET or is of heat sink? So generally the area we consider is for MOSFET here where we need to remove the heat. So, we have talked about heat pipe cooling and how do we do.

So we take we transfer the heat. There is a mechanism; there is a part that there is some liquid filled at the partial pressure, partial vapour pressure. So, it takes the heat to get converted into gaseous space, cool down at ambient and then again that fluid keeps on circulating. So, that is how heat pipe functions, generally made of good conductor generally copper made.

Student: And what is the liquid inside?

Professor: Generally water but at partial pressure, partial vapour pressure so boiling point comes down. For 1 atmospheric pressure, the boiling point of water is around 100 degree centigrade. However, if you reduce the pressure, vapour pressure or partial vapour pressure we say; vapour pressure will generally say. If you reduce that means you reduce the ambient pressure, like at hill station; your water will boil at lower temperature 95 degree or 90 degree.

If you further reduce, it may boil at 70 degree centigrade; so that concept is used here. So, you partially vacuum the pipe then filled with some small amount of water. Now, it can boil at the lower temperature, now it can convert into vapour and that travel down there is a path there to outside ambient. It releases the heat there, convert back to the liquid and…

Student: And what do we ensure it only goes in that (())(33:58)

Professor: No, it is a just what you say capillaries action, very small capillaries type of tube it would be.

Student: (())(34:09)

Professor: You have to be little bit loud. The pipe, which material of heat pipe is made of that is a question? Generally it is made of copper generally. Because it needs high thermal conductivity also, then only it can release the heat to outside and can also circulate the heat into the pipe. So, the thermal conductivity 10 to 100 times of the copper, even though the copper is we measure the efficiency in terms of how much thermal conductivity has increased because of this.

So, it is made of copper, but because the phenomenal of moving the fluid inside and changing the phase, the effective thermal conductivity of the copper if you consider only the copper, and then some other material, you can consider the other material thermal conductivity has gone up to 100 times by this phenomena. What will happen if thermal conductivity increases what will happen? The heat transfer rate it will increase; Q is nothing but K a delta T.

So, effectively we are increasing K by a mechanism inside. Now, third one is by decreasing the contact resistance by filling with a some better thermal conductive material. So, we use thermal paste even between the cells, we use the thermal paste to increase the heat transfer. Next one is phase change material which we discussed earlier also, how does it do? It changes its phase.

Because of phase change the high amount of energy can be absorbed and can be released; both whatever you require. If you want to absorb energy, then it will change the phase from either solid to liquid or liquid to gas, if you are absorbing. If you are releasing the heat, then reverse will happen; from gas it will convert into liquid and from liquid it will convert into solid.

Temperature remain constant at that time like boiling, solidification. So, maintaining the same temperature you can still takeout the large amount of heat or you can put back large amount of heat. By utilizing the phenomena of phase change and we say also it is a latent heat; there is something known as sensible heat. Sensible heat happens because of this temperature change and latent heat same temperature but because of the phase change.

Why operational temperature minus 30 to 150 degree C? Quite efficient if we use it judiciously considering the environmental factor, the PCM becomes one of the best thermal management systems for battery because you do not utilize the energy of the battery.