Fundamentals of Electric Vehicles: Technology and Economics
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Lecture - 60
Thermal Design - Part 2

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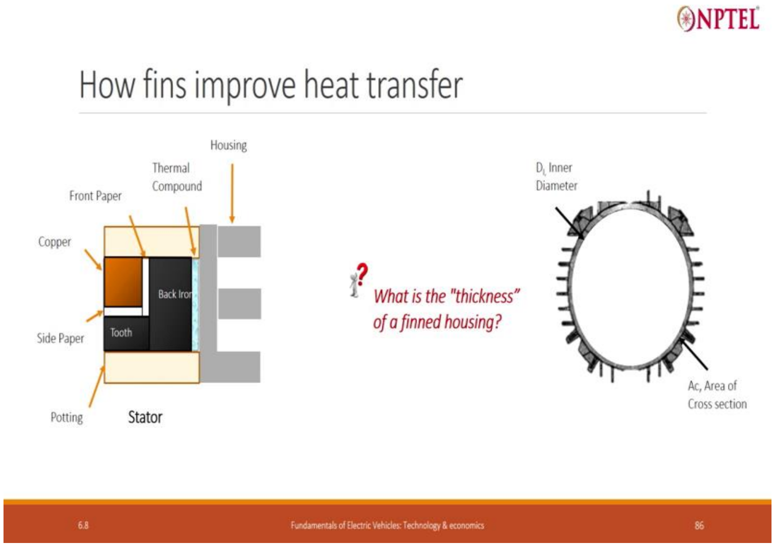

Now, we will attach to it the rest of the motor and also look at the fins in the end. So to this portion that you just now saw, I am attaching the back iron, and then the junction, and then the housing, which is comprised of fins also. And all the air gaps around I have the option of just leaving it as it is or I can fill it with some other material, which is electrically insulating but conducts heat well and that is called potting.

Likewise, this junction here I can simply make it an interference fit and there will be some little bit of air gap there I can leave it as it is or I can do what is called a shrink fit. I will heat the aluminum, expand it, put the stator inside it, and allow it to shrink. That will give me a much better grip and reduce the junction resistance.

Even better, just before doing the shrink fit, I will apply a conducting, thermally conducting but electrically insulating paste, which is called a thermal compound. And then do the shrink fit then there will be no air left and the conduction will be even better. So this is what the whole thing will look like. The open question is housing does not have any defined thickness, it is just varying all over the place how can we model it?

From the inner face of the housing of the housing to the outer face of the housing, there is conduction happening and from the outer surface of the housing to the air, there is convection happening. And this geometry is highly irregular. How can we model this? So this is what the cross-section of the housing looks like.

The inner diameter is known, which is practically the same as the outer diameter of the back iron because they are going as a snug fit. And if I look at the section view of the housing from the geometry of the fins and other things, I know what is the area of cross-section which is the amount of aluminum that is there.

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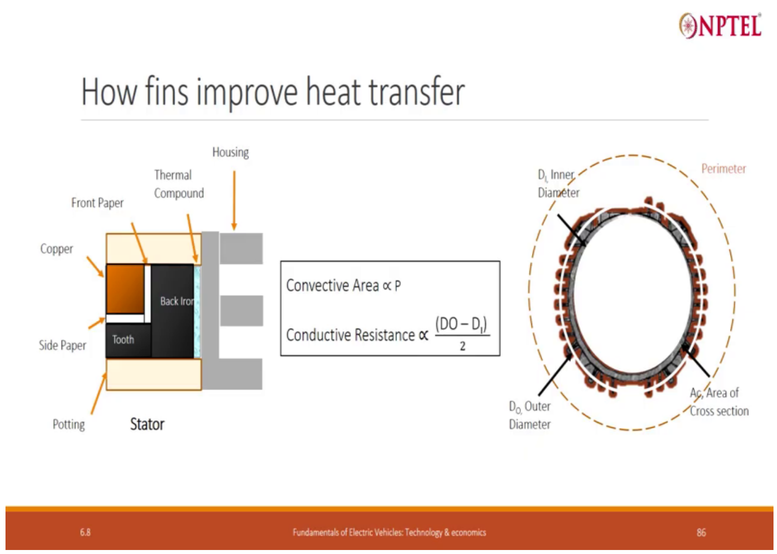

And the periphery of all the fins and the body of the housing, the length of it, I am calling it as a perimeter. The perimeter as you can see is much larger than just the circular portion that is occupied by the body of the housing.

So if I pull out the perimeter and make it look like a circle, it will be actually three or four times bigger than the bore of the housing. It will be very large and that is the whole idea because we an, we want to expose the heat to a large surface area for easy convection.

But if I try to visualize the housing as if it were a smooth pipe, no fins but has the same quantity of aluminum means it weighs the same, every meter of the smooth pipe weighs the same as a meter of this finned aluminum housing, then what is the outer diameter which will give me that?

Which means what is the outer diameter which will enclose the same amount of aluminum? And I am calling that as D o, the outer diameter. And the difference between D o and the D I, the inner diameter is actually the length of path for conduction. Strictly speaking D o minus D I by 2.

So we have two different areas, the D o minus, D o, the o should be small, it is a mistake here. D o minus D I by 2 is the length of the path of conduction. But the area available for convection is proportional to this perimeter, which is much bigger. So you can see that this D o is a little bit bigger than the wall thickness of the aluminum.

So actually the thermal, the conductive resistance is becoming a little bit more maybe a millimeter more but again, it is aluminum, one more millimeter of conduction resistance is not much. But for a small increase in the conductive resistance, I am tremendously increasing the convecting area so I am bringing down the convective resistance. That is the advantage of fins.

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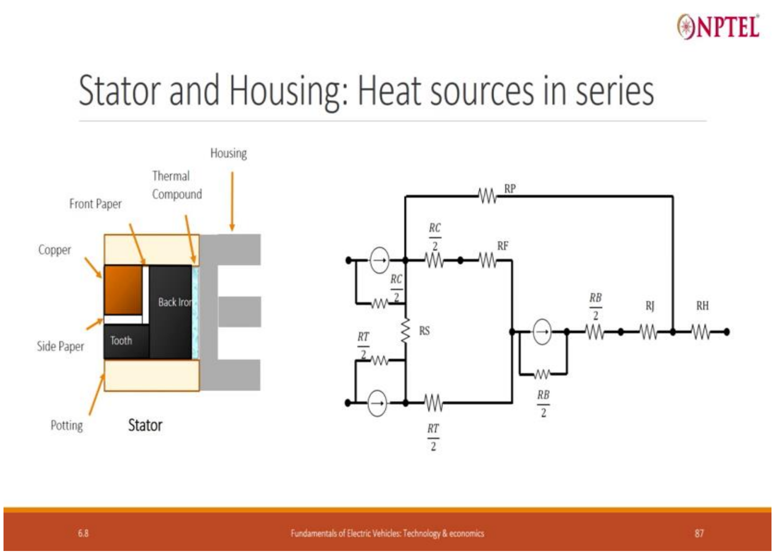

So knowing this, I can expand the thermal circuit that we already had. We already saw that there is copper and there is tooth. And there is heat being generated in both of them and there is a resistance, R by 2 R by 2, the Norton modeling and the copper is going through the front paper and ending up in the, in this point which is the beginning of the back iron over here. The back iron is here that point is this.

The tooth on the other hand directly connects to the back iron, there is no paper in between so that comes here. The back iron is also a source of heat because it also contributes to steel loss and that has been modeled here. RB is the resistance of the back iron, which we can calculate because the back iron is like a pipe, usual formula. And half of that resistance I will put here half I will put there.

And after that, the back iron connects with a junction which offers a resistance RJ and then it connects with the housing, which offers a resistance RH, which depends upon D o minus D I by 2, what we just now saw. And in addition, there are two parallel paths also for the current, heat current to flow one is from the copper to the tooth through the side paper and another is from the copper directly to the housing through the potting compound RP.

And every one of these, the potting, everything is a pipe. So, once we know what is the lambda and what is the geometry of it we can calculate all of these resistances.

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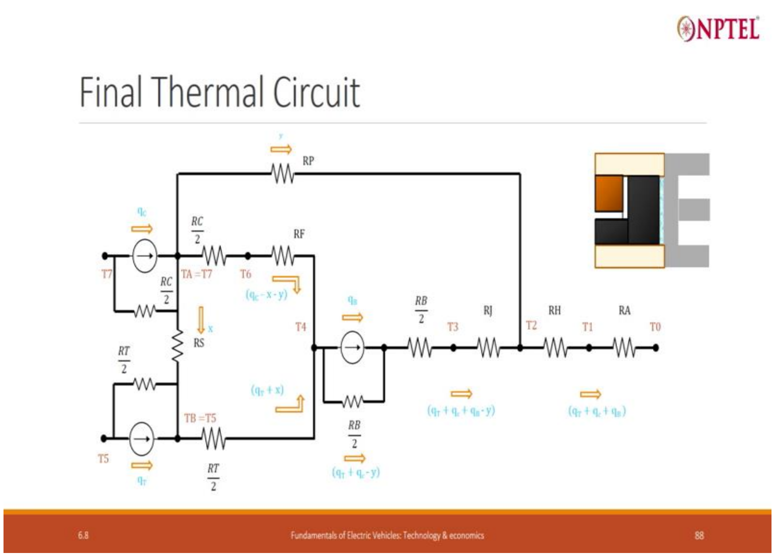

The only thing remaining to add in the final thermal circuit is the air. The, after the housing, there is an air and that is the convective resistance where we can apply the formula 1 by HA and H will depend upon the speed of the air and A depends upon the perimeter, which is much larger. The perimeter provided by the fins. Therefore, it will be much lower than what it would have been without the fins.

Having done that, we can now straight away put in all the values. We know the copper is, the heat current due to copper, I squared R; we know the total steel loss. And if I find that the area occupied by the teeth is let us say, 25 percent of the total stator area then whatever is the total steel loss 25 percent will be the qT value here and the remaining 70 percent will be qB.

So we know qC, qT, qB; we know all the resistances. Now, we can just trace the path of the heat current. qC is flowing here, some of it is getting diverted here, I have called it x; some of it is getting diverted here, I have called it y. What is left is qC minus x minus y, which is flowing here, which comes from Kirchhoff's first law because the total current must be 0. What is flowing in must flow out.

Now, this qC minus x minus y will flow up to this point called T4 and this x will join with qT and flow here, so the current here is qT plus x. Now, this qT plus x and qC minus x minus y will join here, so the minus x and plus x will get canceled. So the current flowing here will be qT plus qC minus y.

And this qC, qT plus qC minus y will be joined with the, by the additional heat generated by the stator, the back iron qB, and so what the current you get here will be qT plus qC plus qB minus y. And qT plus qB is the total steel loss.

And in turn, the same current will flow all the way up to here where it will be joined by this lateral branch of current y, so what you get here is just the sum of the copper and steel loss. Copper loss is qC, qT plus qB is the steel loss. This is the circuit. Is this fine. It is clear?

Student: (())(10:21)

Professor: RS, you mean the direction of x? You can put it as x and solve it. You can assume any direction and if you get a negative sign, it means the direction you originally assumed is wrong. So it is not a problem, you can assume either way, which is what we are now going to do. We can solve this using Kirchhoff's law.

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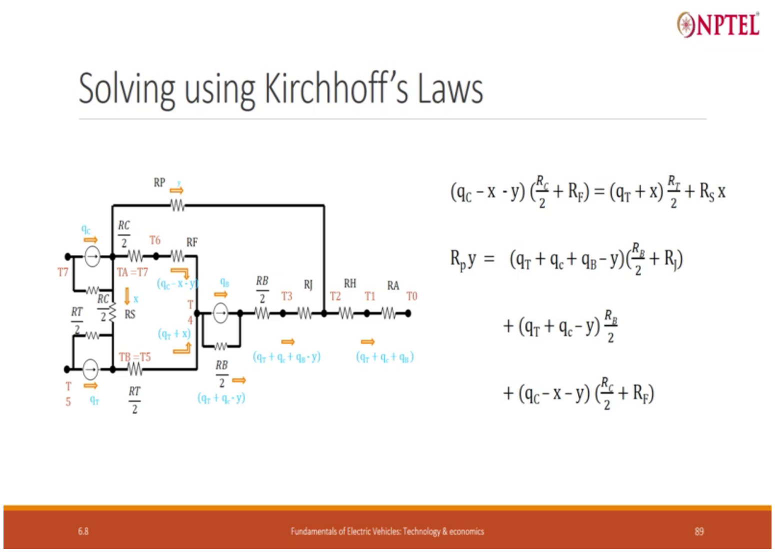

What Kirchhoff's law tells us that, is that between any two points, the voltage, in this case, the temperature difference will be the same no matter which path we travel. So the first path we will take is we will start from this point called T4; T is actually the temperature. The temperature at this point is T4, 4 should be actually a subscript beside it, it has come down in the drawing.

So T4 and the temperature here is TA, the temperature at TA will be higher because heat is originating in the closer to the center and then traveling outwards. Heat always travels from higher temperature to lower temperature. So if I want to find what is TA minus T4, I can travel from the point T4 to TA and calculate the potential drop at every step.

But I can do the same thing by traveling in the other direction also. No matter which direction I take, I must get the same answer. So this T4, TA minus T4 will give me this equation. If I travel in this way, it is qC minus x minus y, the current multiplied by the resistance, which is RF plus RC by 2, this is what you see here. And if I travel in the other direction, it is qT plus x multiplied by RT by 2, that is the first term here, and the second term is x multiplied by RC, RS. So I have got one equation here in which I know everything other than x and y.

Likewise, I can take the point TA and the point T2. And if I travel from T2 to TA, then the temperature difference will be RP into y, which is what is given here. And I can also do the same thing by traveling in this direction and I will get this. Okay?

So just a pair of simultaneous equations and I will know all the currents. And once I know the currents, I know the ambient temperature. From here if I multiply this by RA, remember, I already know what is qT, qC, qB. I can multiply it by RA, I will know what is the temperature T1, which is the temperature at the body, outer body of the housing.

Then if I multiply the same current by the housing resistance, I will get another increment in temperature. If I add that, I will know the inner of the housing. And then I know the value of y, so I can adjust this value and then multiplied by the junction resistance, I will get inside the junction, which is the outside of the stator what is the temperature?

Likewise, I can go at every layer, at every point the different temperatures I can find. I can get the complete temperature profile. And once I have done this in a simple spreadsheet, it is very easy for me to change any value I want; what if I do this, what if I do that, and it is easy for me to converge close to what I think is the optimum value.

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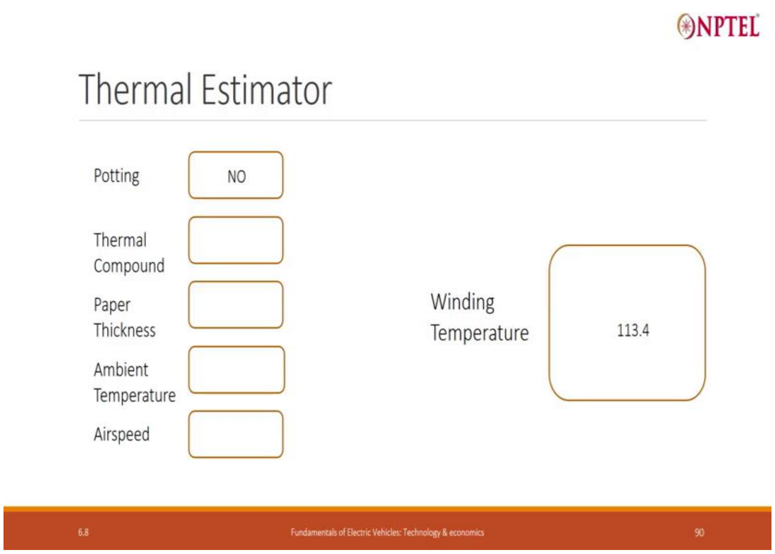

So the way we would do that is what I am trying to show here. Assume that behind this I have got my spreadsheet and I have built a UI in front of it. If there is no potting the winding temperature comes to be 113.4.

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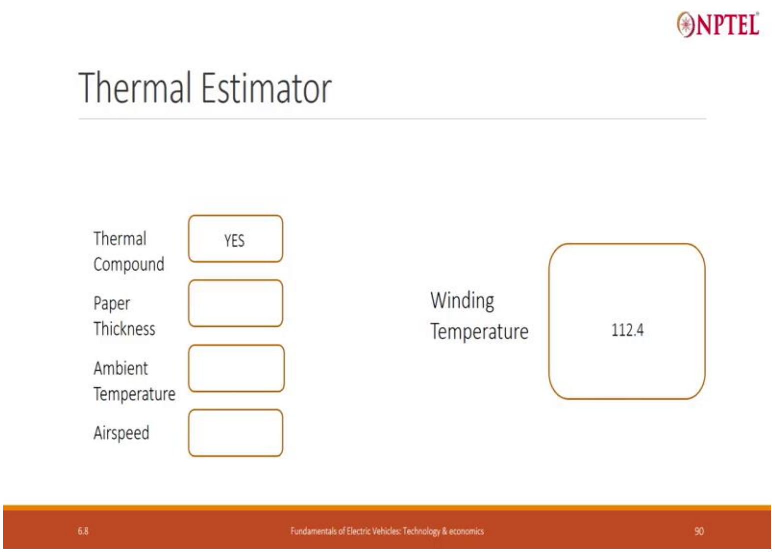

If I do potting, it comes down by 1 degree. Now, if I want to do potting, it is one elaborate step in the manufacturing process. There is some effort involved, there is some cost involved; I have to see whether I want to do it or not. Is 1-degree difference, 1-degree drop in temperature worth all the effort or not?

So it is a judgment call I can take as a designer. I will say, okay, 1 degree the temperature is anyway 112, 113, koi farak nahi padhta. So let me avoid one entire step in manufacturing, I may take that decision. Should I put a thermal compound and shrink fit or not? Should I simply shrink-fit without a thermal compound?

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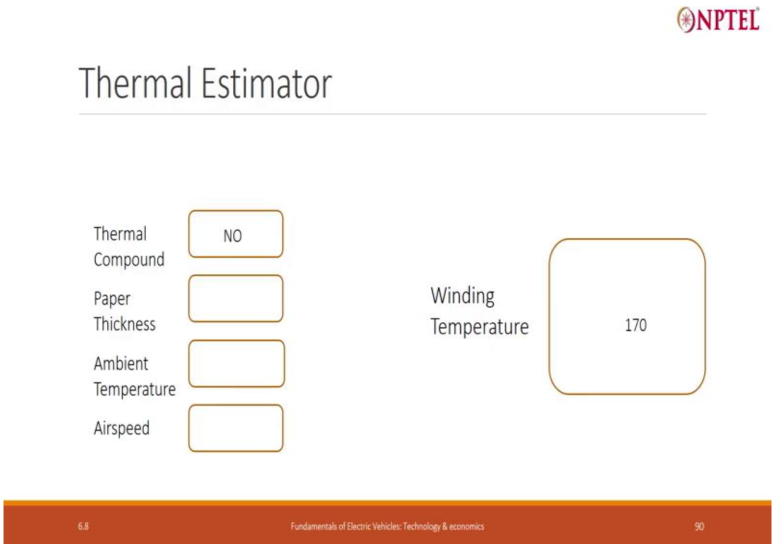

So if I put a thermal compound then I get 112.4 if I do not it shoots up to 170. It is a dramatic increase in the temperature. Can you see that? Just that small point, 0.5 to 0.1 mm thickness of thermal compound makes a world of difference. It is a very critical step in the manufacturing. So I better no matter how painful it is, there is a lot of benefit to be had by doing that operation; I will put the thermal compound.

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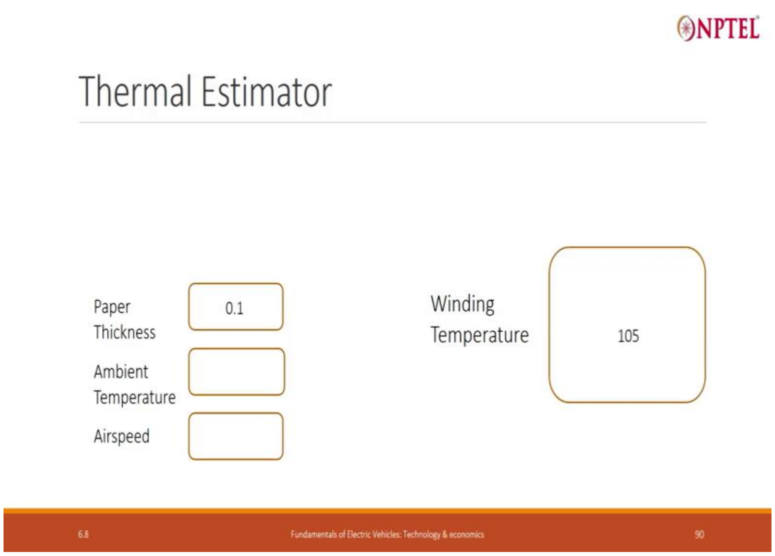

And the paper that I keep, the thinner it is lesser the temperature difference will be. But the problem with having a very thin paper is that during winding, due to the tension of winding, if the paper tears then there is likelihood of the winding shorting with the ground.

So if I want a safe design, I will use a thick paper. But the problem is the thick paper will also cause a build-up in the inner temperature. So I can select different thicknesses and see what happens. If I use a 0.1 thickness of paper, I get winding temperature as 105.

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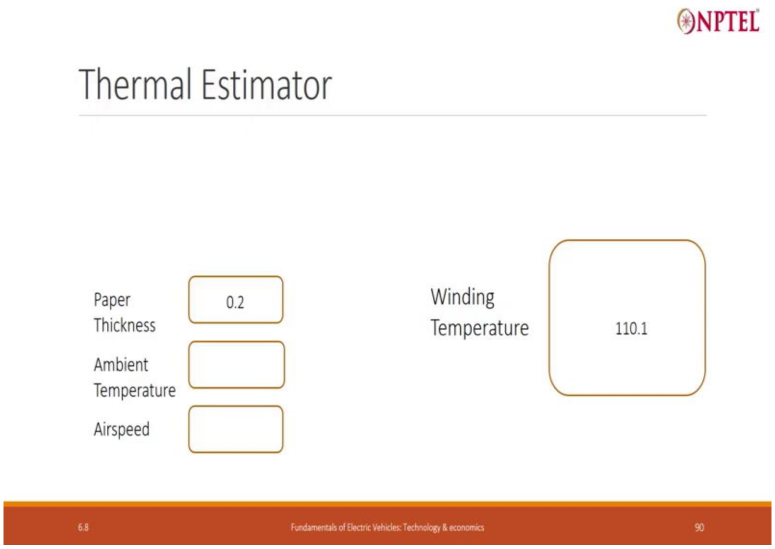

If I use 0.2, I get 110.

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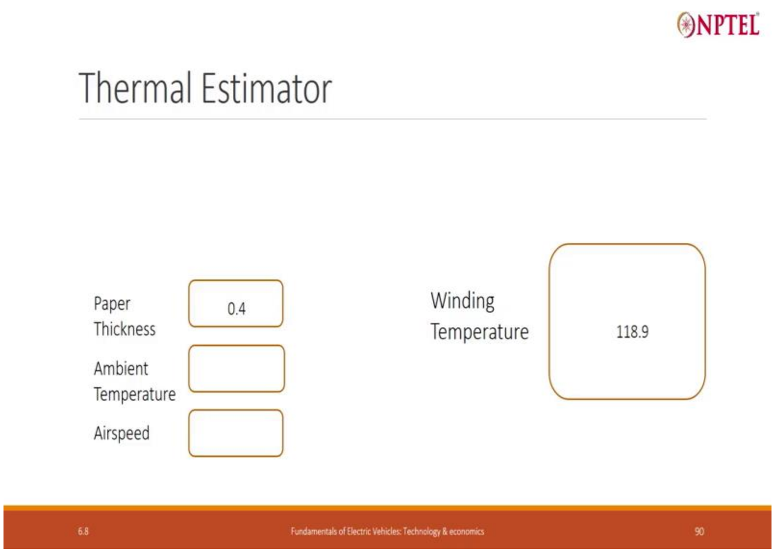

0.4, almost 120.

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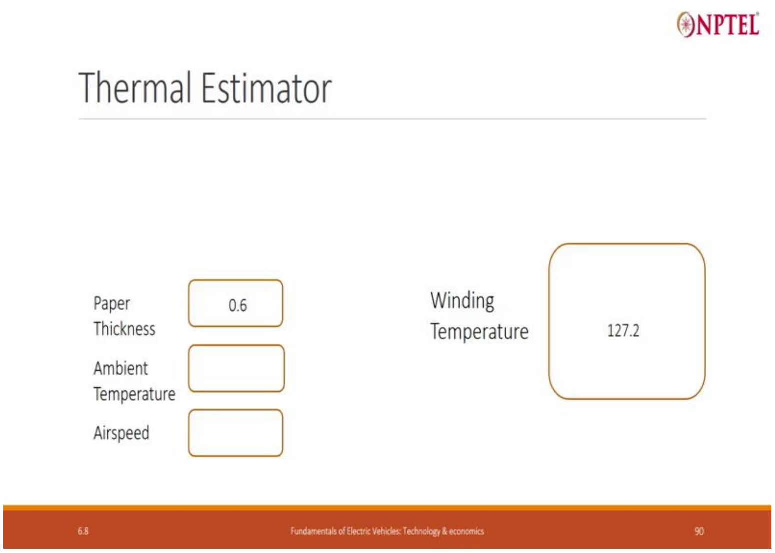

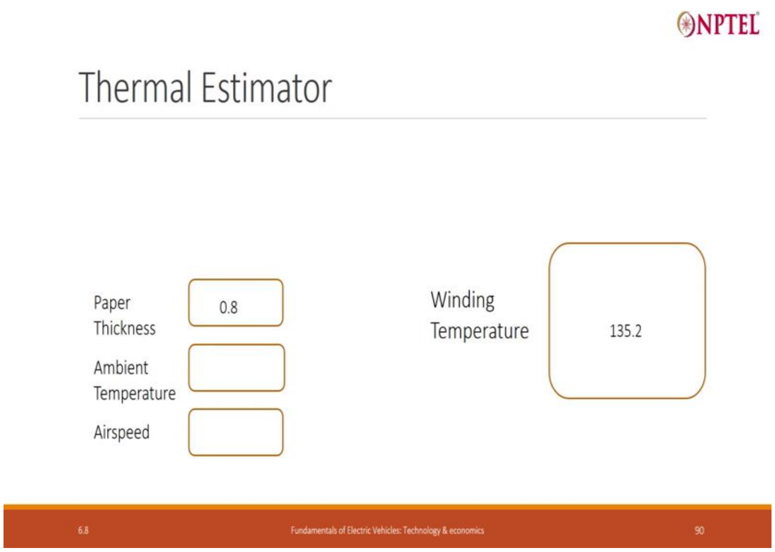

0.6, 127, 135. Based on what I think is an acceptable temperature that I want to have, I can select the thickness of paper that I want.

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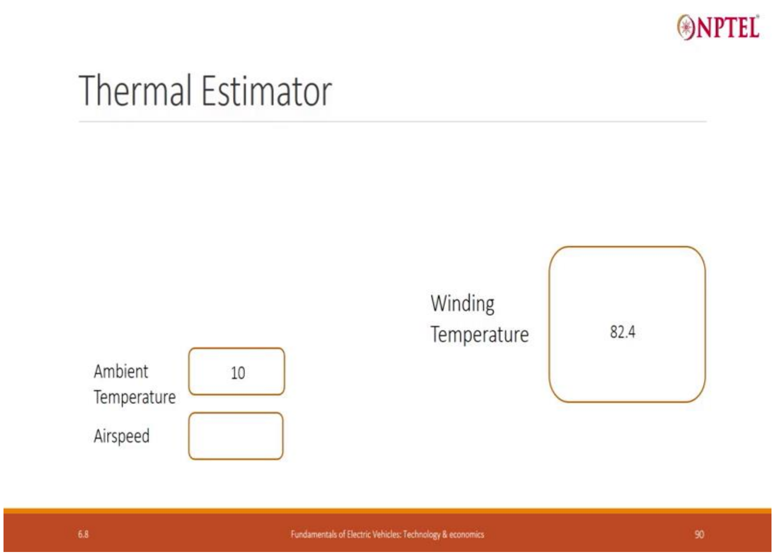

And I have modeled the whole thing assuming that the ambient temperature is 10 degrees, which you will probably find in Ladakh, not in Chennai. What if the vehicle is operated at a higher temperature? If it if I am running this motor in Ladakh, the temperature will be 82, the winding temperature.

We are worried about the winding temperature because that is the hottest part of the motor and also, the thermal limit of the insulation and everything comes from what is the peak temperature. And another reason why we are looking at the winding temperature is that the winding is very close to the rotor. And either on the surface of the motor, of the rotor if it is an SPM motor there are magnets or just a couple of millimeters inside the rotor, inside the steel are the magnets if it is an IPM.

So whatever is the winding temperature will directly impact the temperature of the magnet. The magnet temperature will normally be about 5 degrees lesser than the winding temperature because they are very near each other and just there is a fraction of a millimeter 0.5 mm, 0.8 mm of air gap that is separating them.

So the winding temperature defines the highest temperature that I will find inside the motor. It is also almost equal to the magnet temperature and if a magnet gets hot, it gets demagnetized and that will lead to a severe degradation in the performance of the motor. So this is the temperature that we like to monitor very carefully.

So in Ladakh, I have no problem 82. Normally, magnets come with a rating and we would generally go for a magnet which can comfortably withstand 120 or even 150. If I am willing to pay a lot more money, I can get magnets which can withstand up to 180 degrees but they will be a lot more expensive. So in design, we always try to optimize between performance and cost. So we have to see which is the combination that works well for us.

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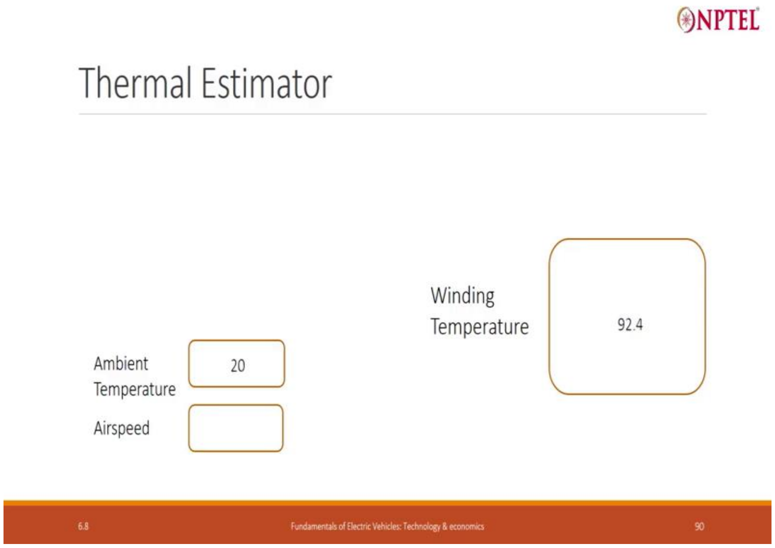

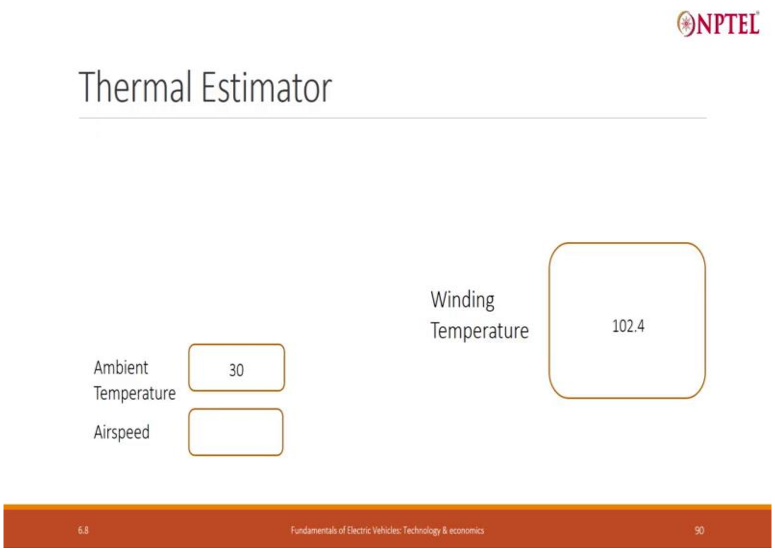

So I have no problem in Ladakh but if the temperature keeps rising by 10-10 degrees, you will find that that winding temperature also increases by the same amount. That is because if you look at the, if you recollect the thermal circuit, we are using the ambient temperature as some sort of a ground level, base. And then, every resistance along the way leading up to the winding is one step increase.

So the increase in temperature from the air to the winding is not changing, if the ambient temperature rises to the same extent, the winding temperature also will rise. It is only a shift of the datum. But having said that, it is not that when the ambient temperature rises significantly, actually the winding temperature will rise more than the ambient temperature for one simple reason, as the temperature increases the resistance of the copper also increases, therefore, the qC term that is there in our thermal circuit will also increase. So the heat flux itself increases. So but that is a minor effect.

If I have a significant difference in temperature like 30, 40 degrees then I will find that the winding temperature increases not by 40 degrees but by 45 degrees.

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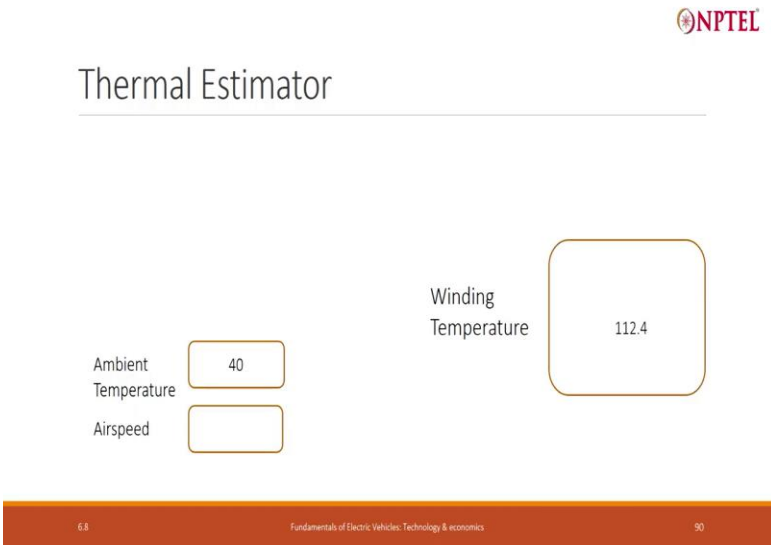

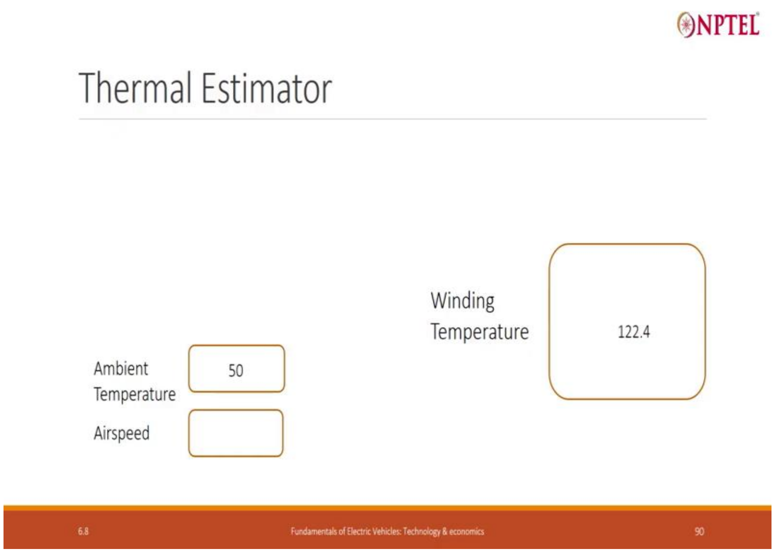

So now this is what is the effect of the ambient temperature and if I say that I want my motor to be designed to be fit for running at 50 degrees, and if my magnet is rated up to 120 degrees then this tells me that I am just on the borderline, I am oaky, the winding is 122. So the magnet is likely to be about 117; 5 degrees lower, I am just there.

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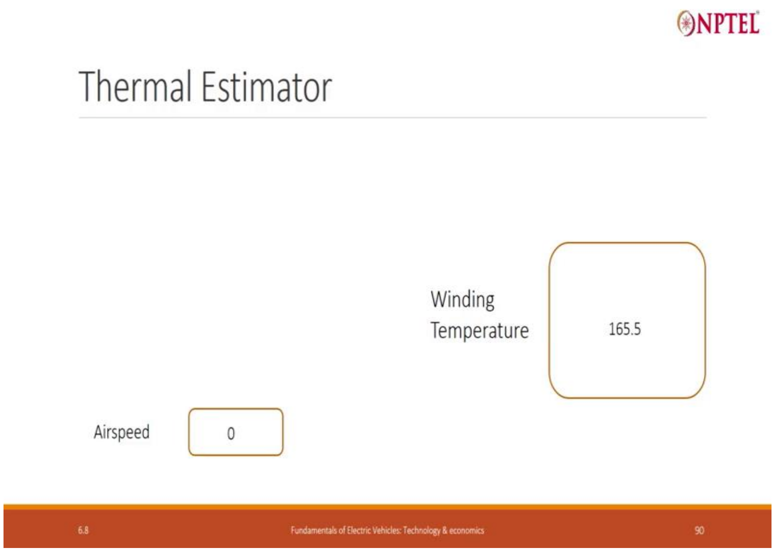

And then airspeed. If there is no air at all, the winding temperature goes up a great deal.

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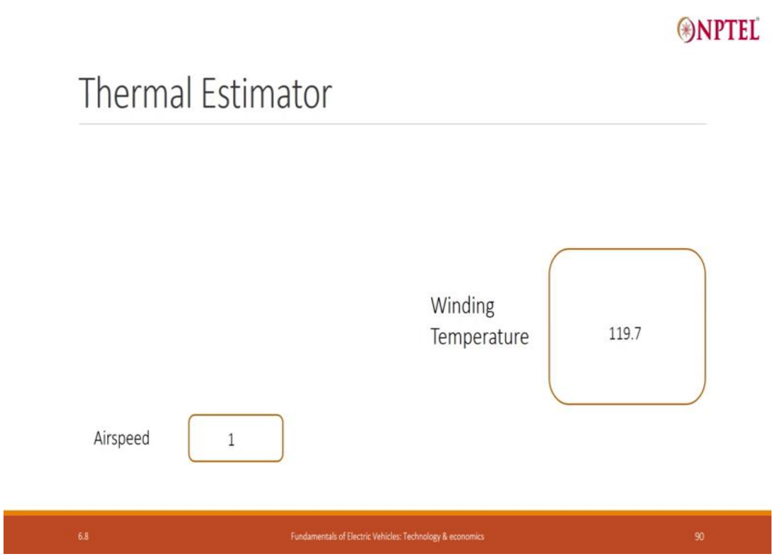

If even a little bit of air is blowing, dramatically the H will increase. So you see that from 165, it came down to 120; 45 degree is the difference between air not blowing and blowing at a very gentle speed of 1 meter per second.

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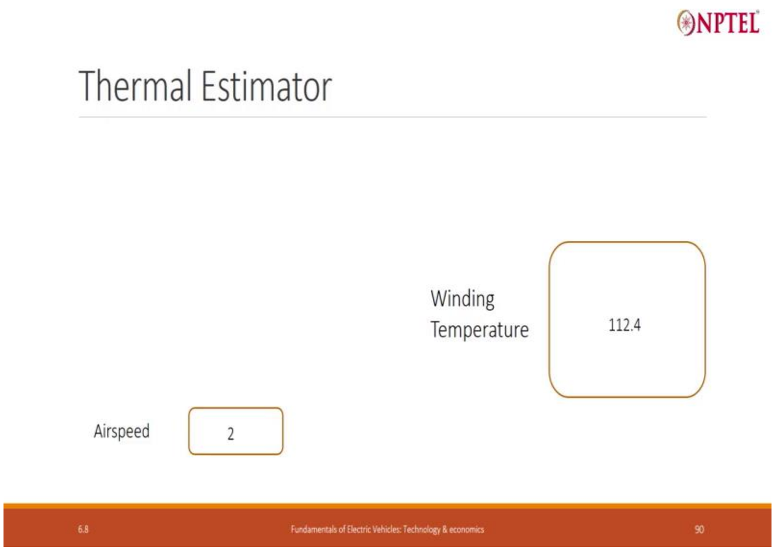
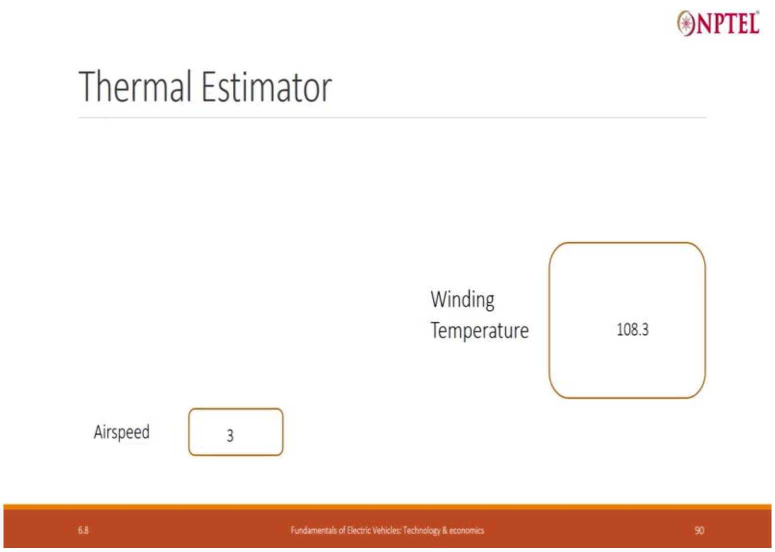




Thermal Estimator

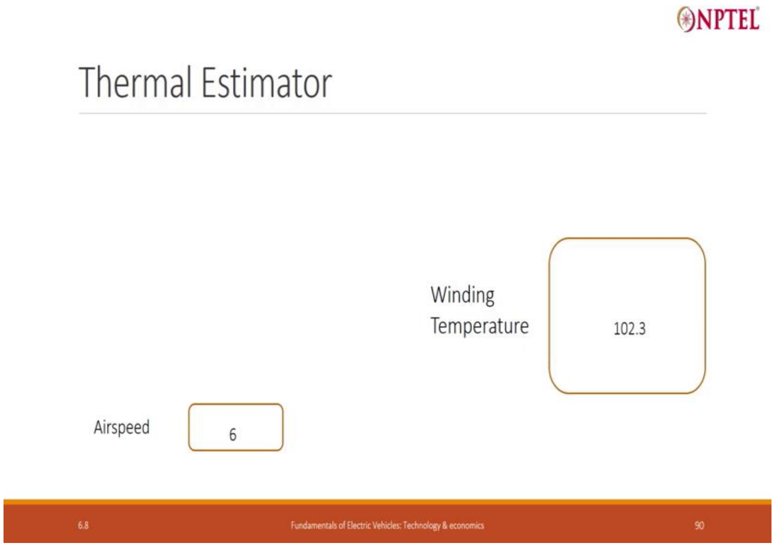
Winding Temperature: 105.7

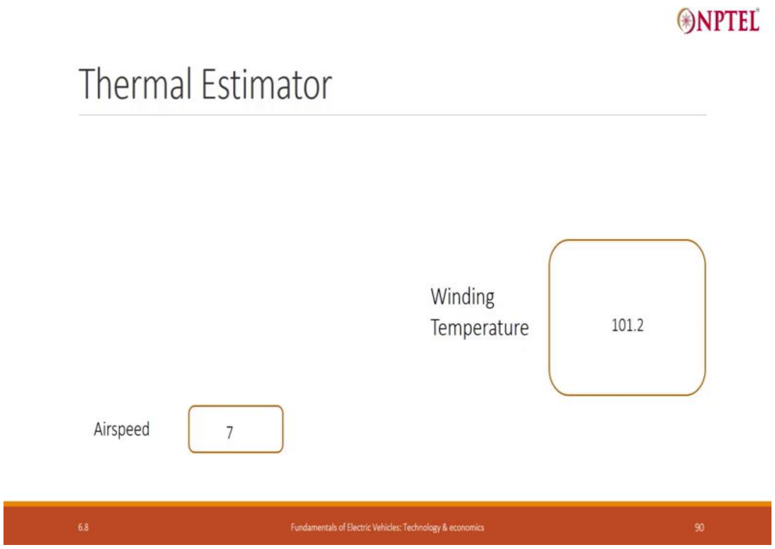
Airspeed: 4

Thermal Estimator

Winding Temperature: 103.8

Airspeed: 5





But if I increase the airspeed, things get better but not so dramatically better. And to increase the airspeed means I have to put effort in pumping the air. So we have to see what is the optimum and I may decide that since I can go up to 120 degrees for the magnet, an airspeed of 2 is sufficient. I do not need to go faster and really you will see that beyond 5 when wind is blowing at 5 meter per second, it is about 104 degrees, the winding temperature. If I make it 6 it just comes down by a couple of degrees. Fine?

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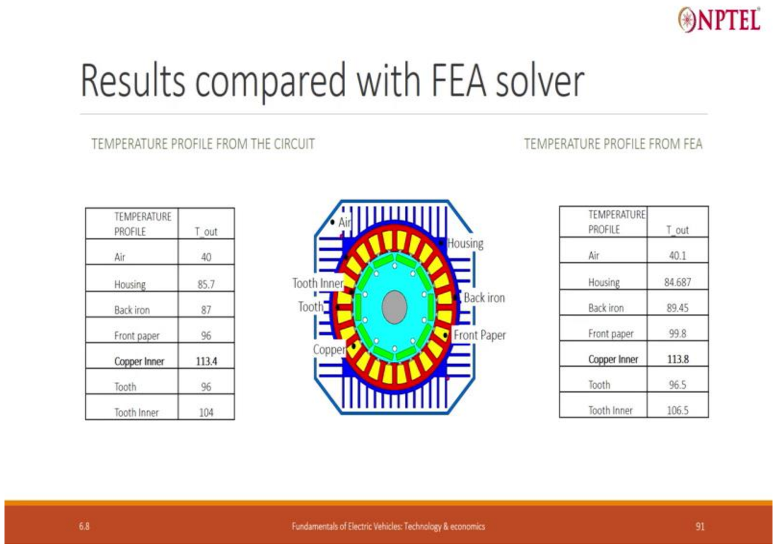

So that is the diminishing returns that we saw that you get by increasing the airspeed. So beyond the point, it is not worthwhile to increase the airspeed. Now, after we have sufficiently optimized the design, our model which is based on a spreadsheet is based on lot of simplifications in our assumptions.

The FEA will be a lot more accurate, but lot more time-consuming. But after we have significantly optimized the thermal design, we can then run the final design on an FEA solver and compare. And for one particular example where we did that, I am showing you the results and you will see that the main parameter of interest which is the copper, has been very accurately predicted by our spreadsheet in comparison with the FEA. And with much less effort.

The both the experiments were done for about 40 degrees ambient temperature. The housing temperature is probably different by 1 degree between the spreadsheet and the FEA and in between the geometry and other things we have not, we have modeled them somewhat simplistically. So you will find a little bit more difference. For example, back iron here is 89 and 87, so you are finding something like two and a half degree difference in the prediction but all that is all right does not really matter for us.

So what I am saying is that the circuit diagram and the spreadsheet that we used to model the circuit diagram is very useful for quick iterations. It is not as accurate as the FEA but much quicker and much simpler. And therefore, in the early stages of design, it is good to build this model and change lot of parameters in different ways and optimize the design and then do the final refinements through FEA modeling.

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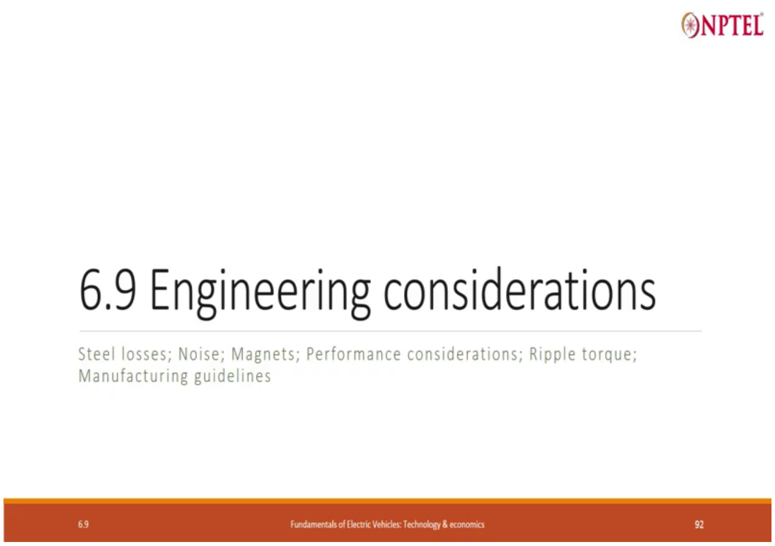

So far are we fine? Is there any questions?

Student: (())(24:14)

Professor: Yeah. So the point that is getting made is that FEA is particularly useful when we use it for more complex environments and do a 3D simulation and that will be very difficult to model on a simple spreadsheet.

The 3D modeling will take into account the fact that the motor is inside a bonnet and the air around it is not at a uniform temperature. In some places, the air is hotter and some places the air is colder, and maybe it is flowing faster in some places, slower in some other places. And again, along the length of the motor, we have assumed that there is a uniform velocity but actually, at the origin from where the air is blowing, the velocity of the air will be high but as it flows, it is also diverging outside radially, so the velocity will decrease.

All of these things in 3D to be modeled is what will give us a very important new information, which is called hotspots. There will be certain locations, for example, the windings are made of number of strands of copper wire, which are all packed in the slot and there will be some localized areas where heat is getting generated but not getting evacuated fast enough, whereas in some other places whatever heat is getting generated is getting evacuated fast enough.

What our spreadsheet model tells us is the average rate of evacuation. But these localized places where heat is not getting removed quickly enough will tremendously rise in temperature and they will cause localized vulnerable points thermally and can lead to a breakdown.

So I am not discounting the value of the FEA simulation at all, all I am saying is that in the early stage of design, it is very time-consuming to do the simulation at (every); for every small design change that we make, we can rapidly do a dozen different changes and come close to what we think is an optimal design and it is also intuitive because we have built the thermal circuit and we can see almost like moving a slider and saying, hey, if the paper thickness becomes like this, that is what happens to a temperature. That kind of optimization, it will give us a strong intuition for.

Having done that, then we must definitely do the detailed thermal simulation, preferably in 3D to locate these particular failure modes which will lead to hotspots. So that is a valid point well taken. Any other question?