Process Integration
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Module - 5
Pinch Design Method for HEN Synthesis
Lecture - 9
Driving Force Plot

Welcome to the series of lectures on process integration. This is module 5, lecture 9 and the topic of the lecture is driving force plot. We have seen that whenever a problem given to us, a number of visible HENs can be designed for that given problem, but all the HENs, which are feasible, HENs will have different heat transfer area. The question is why is it?

So, why they exhibit different heat transfer area; investigation into this matter will show that these HENs are utilizing differently the driving force, which is available to them. As they are utilizing differently, they have different area, and obviously when there is different area, there will be different cost. So, the pinch analysis tries to distribute this driving force properly, so that the design will have less area. So, today we will investigate why the different feasible solutions exhibit different area. To start with, let us take a problem, which is there in the screen.

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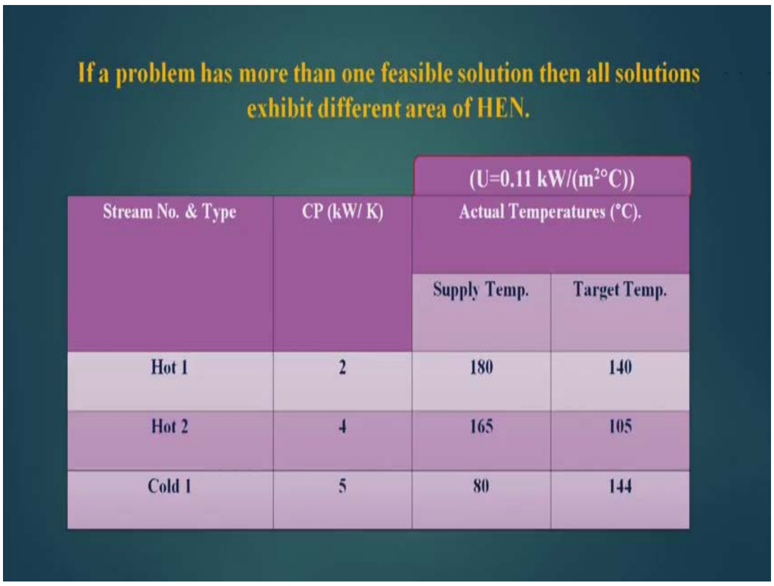
If a problem has more than one feasible solution then all solutions exhibit different area of HEN.

Stream No. & Type	CP (kW/ K)	Actual Temperatures (°C). (U=0.11 kW/(m^2°C))	
		Supply Temp.	Target Temp.
Hot 1	2	180	140
Hot 2	4	165	105
Cold 1	5	80	144

It has got 2 hot streams and 1 cold stream. The U, which is the heat transfer overall heat transfer coefficient is taken to be 0.11 and this is same for all the streams.

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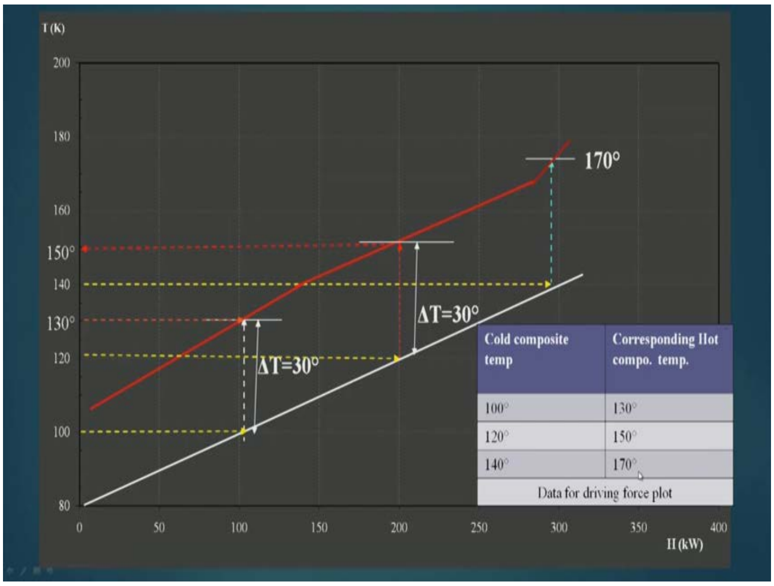

To do so we will plot a driving force plot. This driving force plot has been plotted using the hint software. The driving force plot is basically a plot between the cold temperature and the hot temperature that means cold stream temperatures and hot stream temperatures. Now, the present diagram, which is on the screen, is not a driving force plot, but we will like to extract the value will information for a driving force plot from here. Now, this is 100 degree centigrade as this temperature, the driving plot force plot is the driving force is 30 degree centigrade and this temperature 120 temperature, the driving force is again 30 degree centigrade. Here, at this temperature 140 degree centigrade, the driving force is 170 degree centigrade.

So, when cold composite temperature is 100, then hot composite, corresponding hot composite temperature is 130 degree centigrade. Similarly, when the cold composite temperature is 120, this is going, it is meeting here at 120. When we go vertically upward, this is hot composite curve, this is 150. So, 120 and this is 150.

Similarly, when we at 140 degree, when we move to this cold composite curve, then if we rise vertically to the hot composite curve, the hot composite curve temperature is 170. Now, we have cold composite curve temperatures and corresponding hot composite curve temperatures. Now, similarly, you can have many points. We can calculate many points from these composite curves and you can draw it, the x axis as cold temperature and the y axis as hot temperature. Now, let us take a HEN design for the problem, which has been given in the stream table. Now, this is we call design one.

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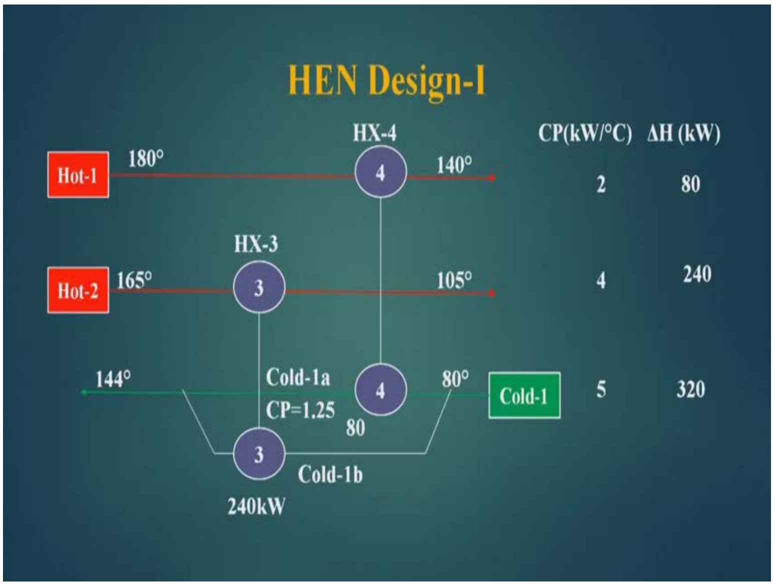

So, we will place heat exchangers based on the pinch rule. Now, we can place a heat exchanger like heat exchanger number 3. Then, we can have heat exchanger number 4. So, this stream which has C P value as 5 is broken into 2 parts, split into 2 parts. This is C P is 1.25. So, this C P which is cold 1 b will have 5 minus 1.25 the value of the cp. This is 80 kilo watt heat exchanger and this is a 240 kilo watt heat exchanger.

So, this is a feasible design. Similarly, we can develop other feasible designs.

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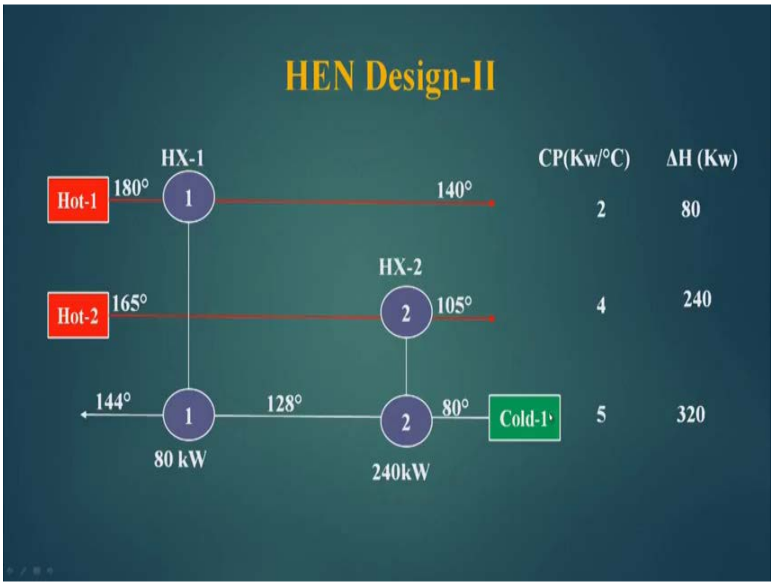

This is the design two. This is design two same hot and same cold. So, this is design two and here also the heat exchanger 1 has got 80 kilo watt and this is called 240 kilo watts.

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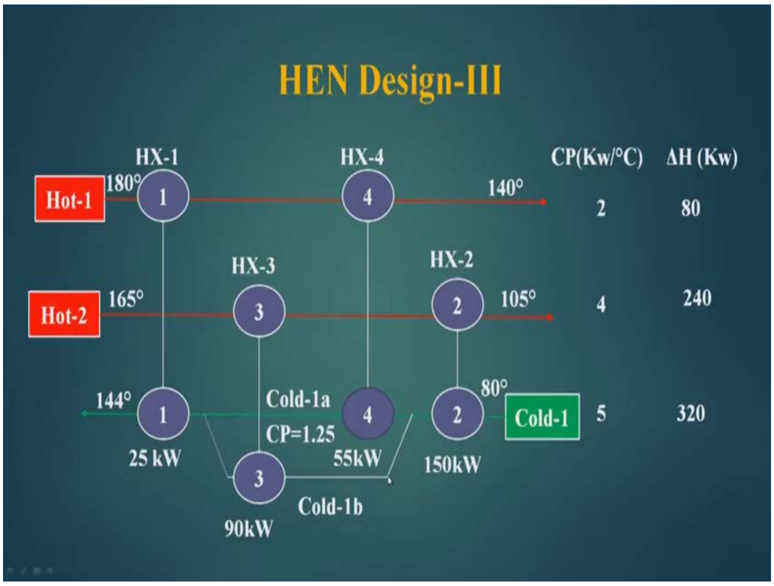

Now, this is a third design where cold is now split into 2 parts, cold 1 a, cold 1 b. It has got 4 heat exchanger; heat exchanger number 1, 25 kilo watt, heat exchanger number 2, 150 kilo watt, heat exchanger number 3, 90 kilo watt and heat exchanger 4, 55 kilo watt. So, we have seen that for a problem, we have 3 heat exchanger networks available and all the 3 heat exchanger networks are feasible in nature. Now, let us see the temperature profiles of the heat exchangers in the heat exchanger design one.

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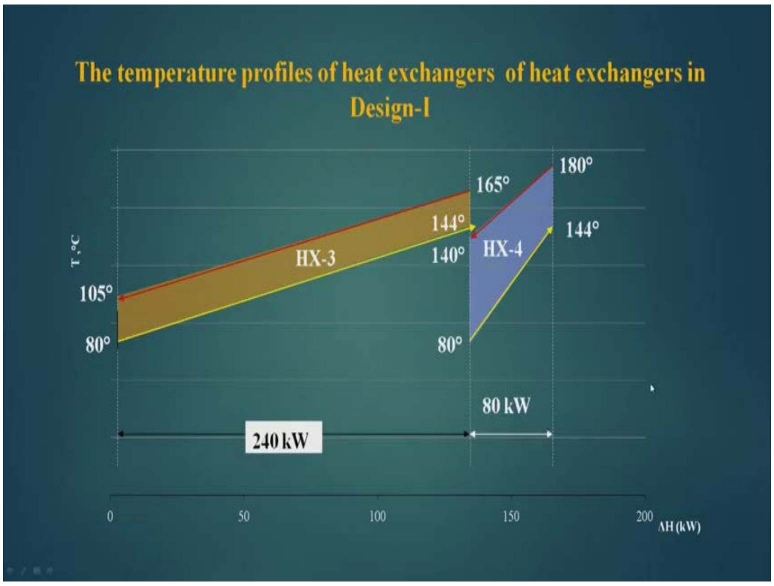

So, heat exchanger design has got 2 heat exchangers called heat exchanger number 3 and heat exchanger number 4. At one end, it has got a temperature of 80 and 105; that means the hot stream is coming from 165 to 105 and the cold stream is rising from 80 degree centigrade to 144 degree centigrade. This is for heat exchanger number 3 and the capacity of the heat exchanger is 240 kilo watt.

Similarly, there is a second heat exchanger, which is heat exchanger number 4 we call it here. At the cold u, let this is 80 degree, cold outlet is 44 degree, hot inlet is 180 degree, hot outlet is 140 degree and this capacity is 80 kilo watt. Similarly, we can go to design two. Here, there are 2 heat exchangers called heat exchanger number 1 and heat exchanger number 2.

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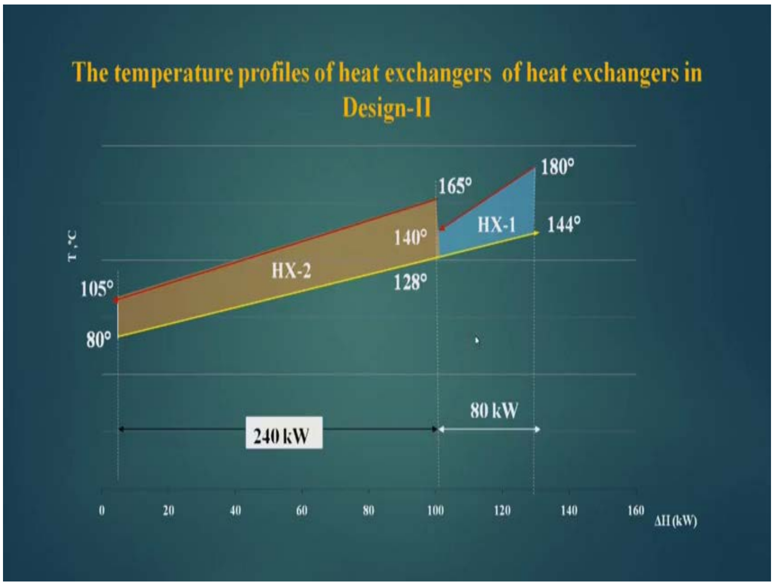

Heat exchanger 2 is to 140 kilo watt. Here, the cold in let temperature is 80, outlet temperature is 128, and hot inlet temperature is 165 and 105 outlet temperature for heat exchanger number 2. For heat exchanger number 1, the cold inlet is 128, outlet is 144 degree centigrade, hot inlet is at 180 degree centigrade and outlet is 140 degree centigrade. This heat exchanger is a small heat exchanger compared to this and is having a capacity of 80 kilo watt.

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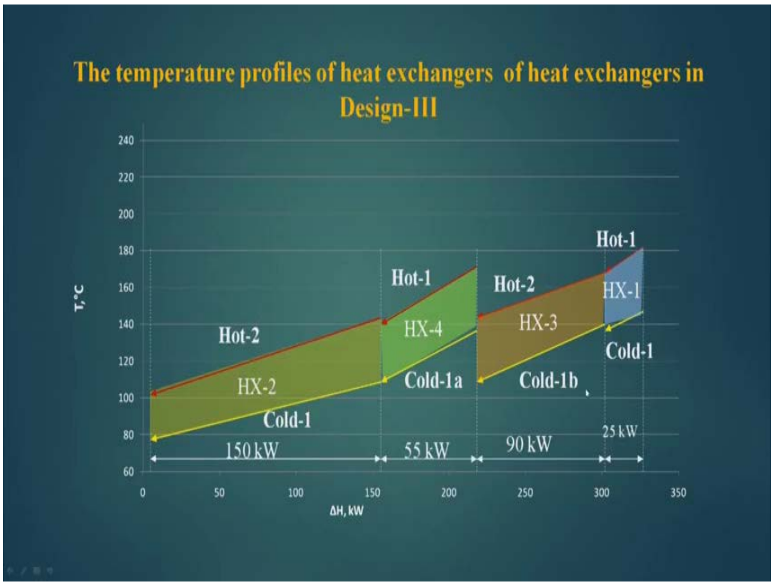

Similarly, if we go for the third heat exchanger, third heat exchanger, third design has 4 heat exchangers; heat exchanger number 1, 2, 3, 4 and born as a capacity of 25 kilo watt, 250 kilo watt, 390 kilo watt and 455 kilo watt. Their input output temperatures are shown. Now, we have seen that different designs have different number of heat exchangers and the input output temperatures are different. So, they are having the driving force differently. So, this was that are the exchangers taking place, this is hot 1 is exchanging heat with cold 1a in this heat exchanger number 1. Hot 2 is exchanging heat with the cold 1 b, which is split stream of the cold 1. This is it will hot 1 and cold 1 a and this is hot 2 and cold 1 b.

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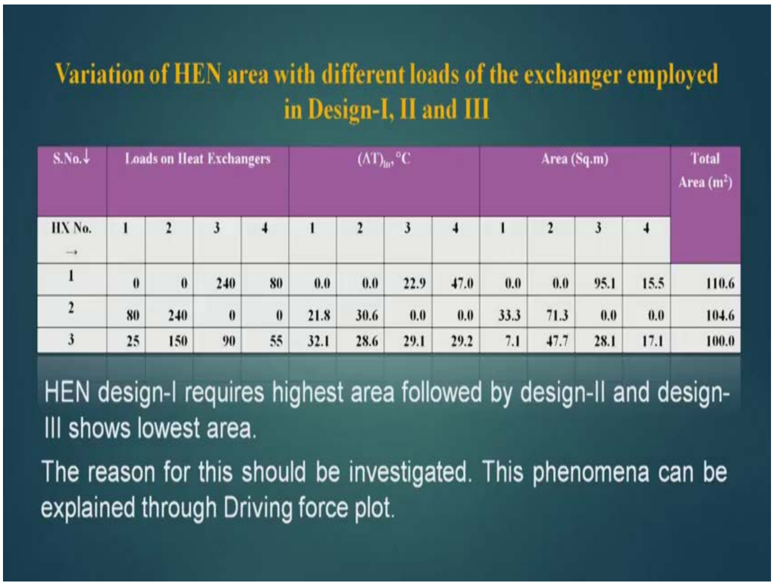

Now, this table has been created for all these 3 designs. This shows heat exchanger number that is H X 1, H X 2, H X 3, and H X 4. This shows delta T, login temperature difference for heat exchanger 1 H X 1, H X 2, H X 3, H X 4 and this shows the area of H X 1, H X 2, H X 3, H X 4. Then, this shows the total area.

Now, this shows the feasible design; design one, design two, and design three. Now, in the design one, heat exchanger 1 and heat exchanger 2 are nil. They are not there. Heat exchanger 3 is there, which is consuming 240 kilo watt that is capacity. There is a second heat exchanger, which is called heat exchanger 4 has got 80 kilo watt capacity. Now, obviously 1 and 2 are not there. So, there will be a node delta T allen for that log mean temperature difference 0, 0 and 240, the capacity of heat exchanger is 240 kilo watt. It is utilizing 22.9. The log mean temperature difference value is 22.9, where as for 80 kilo watt heat exchanger, the delta T allen is 47 degree centigrade.

Now, this data clearly tells that this bigger heat exchanger, this is 240 kilo watt is utilizing almost less than half of the delta T, which 80 kilo watt heat exchanger is employing. So, 80 kilo watt, the capacity heat exchanger is employing the available driving force for better way. Then, the 240 kilo watt heat exchanger is employing and that is why, this heat exchanger will increase the area of the HEN because it is not utilizing properly the driving force, which is available with it. This we will also see in the figure.

Now, if we calculate the area, the area comes up to the 95.1 for this heat exchanger 240 kilo watt and 15.5 for heat exchanger 80 kilo watt. Now, here also, you can see this is about 3 times the capacity of this, but if you multiply 15.5, 3 times, we will find that this area is form of than that and that is why the total heat transfer area is 110.6 in this case.

Let us go to the design case 2. It has got heat exchanger 1 and heat exchanger 2. This is using 80 kilo watt capacity. This capacity is 240 kilo watt. It does not have exchanger number 3 and exchanger number 4, but here if you see this 80 heat exchanger is using about 21.8 delta T allen and this has got 30.6 delta T allen. So, these 80 kilo watt heat exchangers, so small heat exchanger in comparison to this is utilizing less driving force and the bigger is heat exchanger is utilizing a driving force, which is far better than the exchanger number 1 of the design two.

So, we expect that this design will deep lesser area. So, when we calculate areas, we find that the 80 kilo watt heat exchanger has got 33.3 area meter square and the 240 kilo watt exchanger has got 71.3 meter square. Here, if we multiply the 71.3 into 3, which comes out with the capacity ratio, then whatever figure, I get it should be 99.9, which is far more than the 71.3. Why this has happened? This is because this heat exchanger is utilizing better driving fast. Hence, its area is less. So, the total area becomes 104.6, which is less than 110.6, 6 units less. If I go further to design three, there are 4 heat exchangers here, heat exchanger 1, 2, 3, and 4. If we see the delta T allen of this, this first heat exchanger has got 32.1, second is 28.6, third is 29.1 and for fourth is 29.2.

So, the delta T is utilization is very good. They are always constant while utilizing the driving force because delta T is symbol of driving force. So, the areas computed are 7.1, 47.7, 28.1 and 17.1 and total gets to 100 meters square area, which is the lowest. So, the first and conclusion, which we draw is that for a given problem, there can be many feasible designs when we are employing pinch analysis method or pinch design method.

There can be many feasible designs and all the designs will have different area. This difference in area is due to the utilization of available driving force for the problem. The available driving force of the problem can be seen through a driving force plot. If the exchangers of the designs feasible designs are utilizing is this natural driving force, which is available properly, then the area will be less.

If they are not utilizing it properly, then the area will be more. So, let us see in a different way, the same statement. The design one requires highest area followed by design two and design three. Design three shows the lowest area. This we have seen. The reason for this should be investigated. This phenomenon can be explained through driving force plot. Now, let us see what a driving force plot is.

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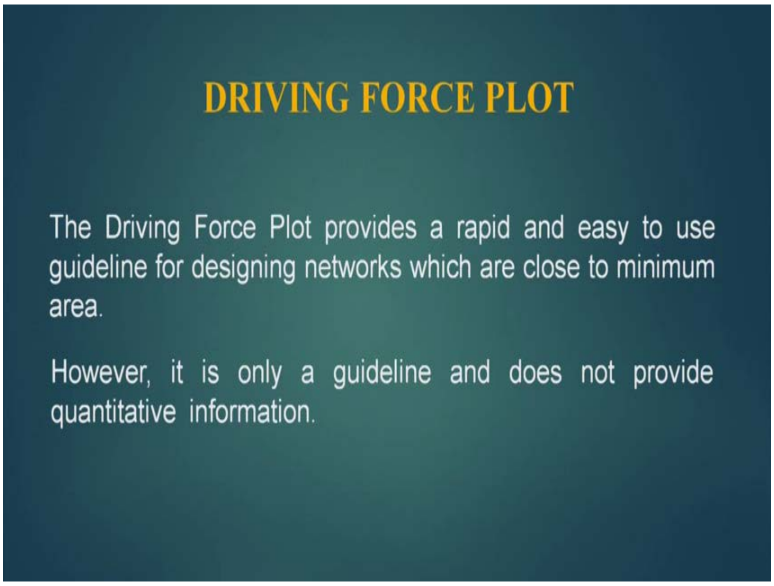

The driving force plot provides a rapid and easy to use guide line for designing networks, which are close to minimum area. Why close to minimum area? If the naturally available driving force is utilized by the design to the fullest extent, then only it will give the minimum area and if the design is not utilizing it, we cannot expect it to offer minimum area. The designs are based on the matches, which we follow in a design because at a point of time, you can have several options for the matches. Whatever options you select affects the area of the heat exchanger network.

However, it is only a guide line and does not provide quantitative information. This we will see why because you see that the capacity of the heat exchanger, which is utilizing the driving force, is also an important parameter. If a small heat exchanger in a network is utilizing very nicely the available driving force, but a bigger heat exchanger is not utilizing properly, so obviously the area will increase. So, how many numbers of heat exchangers are not properly utilizing and what is the capacity of the heat exchanger; both are important in this case. Now, this is the natural driving force, which is available with the problem.

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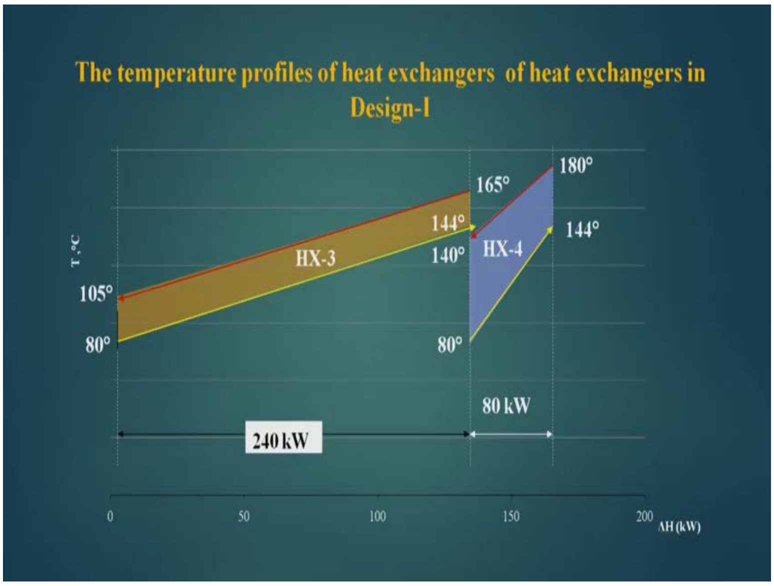

So, this is plotted between T cold and T hot. So, this is the naturally available driving force for the problem and this is plotted using the software hint, which is a 45 degree line, and this temperature which is here and 100 degree for 100 degree cold temperature. The hot temperature is 130 degree. The difference is 30, so from this point to this point. Similarly, here for 120 degree cold temperature, this is the hot temperature for 150 and the difference being 30.

So, this is how the driving force is right and this driving force is the available driving force. It should be utilized through proper match placement. We have seen that we can have different freedom of match placement and that freedom has to be used very properly or judiciously, so that whatever matches we place; that match utilizes the available driving force properly. If it is not utilizing, then we have to pay penalty in terms of increased area of the heat exchanger network.

Now, it is see again, revisit the temperature profiles of 2 heat exchangers, what are, which are utilized in design that is heat exchanger number 3 and heat exchanger number 4. Now, let us see these 2 heat exchangers are how utilizing the naturally available driving force in the driving force plot. So, when we place this utilization of driving force of these 2 heat exchangers into the driving force plot, we get this.

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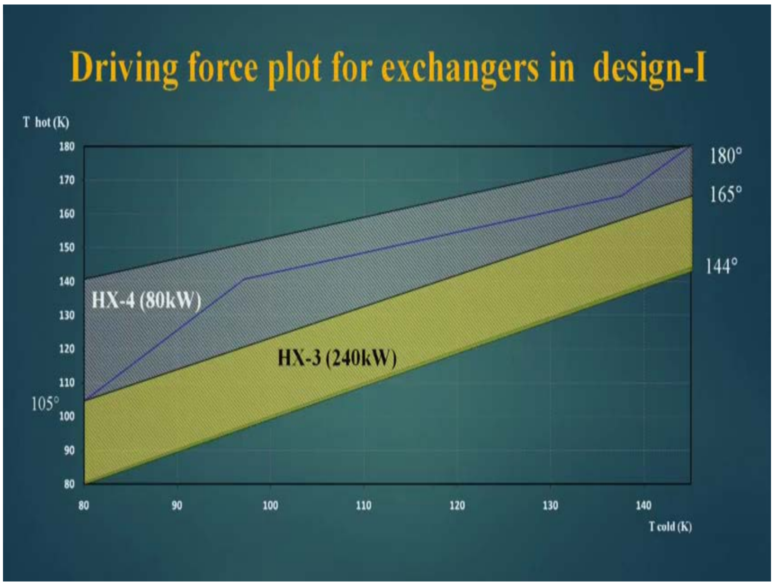

Now, this is the driving force, which is available from here to here and heat exchanger number 4 is utilizing the driving force properly. In fact, it is utilizing it more than the available driving force, but its capacity is less 80 kilo watt only, where as this second heat exchanger, which is H X 3 having a capacity of 240 kilo watt, which is about 3 times more than the capacity of H X 4 is not utilizing the driving force properly. This much amount of driving force is not utilized that means the bigger heat exchanger is purely utilizing the driving force, which is available to it. However, the smaller heat exchanger is utilizing it properly. As the bigger heat exchanger is not utilizing the driving force properly, the design one gives you the maximum area that is 100 time 0.6 meter square.

So, again it is with this, the heat exchangers temperature profiles for design two, when we fold these temperature profiles of heat exchangers to find out how much this design is utilizing the natural driving force, which is available to us, and then this is being plotted to the driving force plot.

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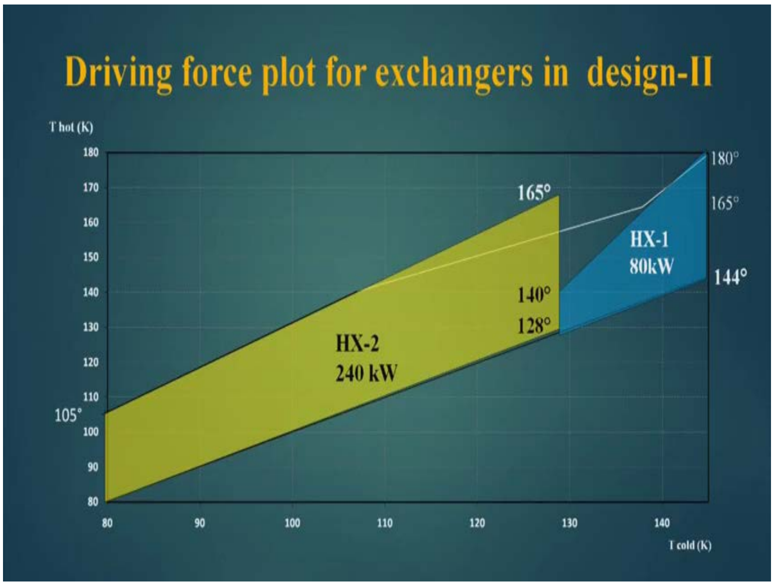

Now, this is the driving force available to us, this line plus this line. Now, we see that the bigger heat exchanger, in fact nicely utilizes to driving force to its fullest extent. This area, it passes the driving force available, but this small heat exchanger which has got a capacity of 80 kilo watt, it is not utilizing this available area of the driving force. So, we expect that its area will slightly increase, if we see the design two, then we find that its area is 104.6 meter square, where as the minimum area is 100 meter square.

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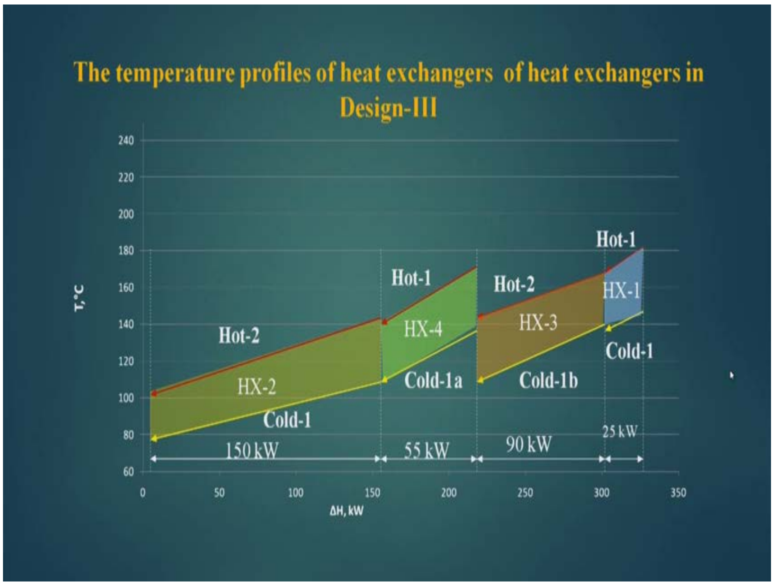

Now, if we go to the design three and see the temperature profiles of this heat exchangers, there are 4 heat exchangers having different capacity, the largest being 150 kilo watt and the lowest being 25 kilo watt. They have different starting temperatures and HEN temperatures exit temperatures.

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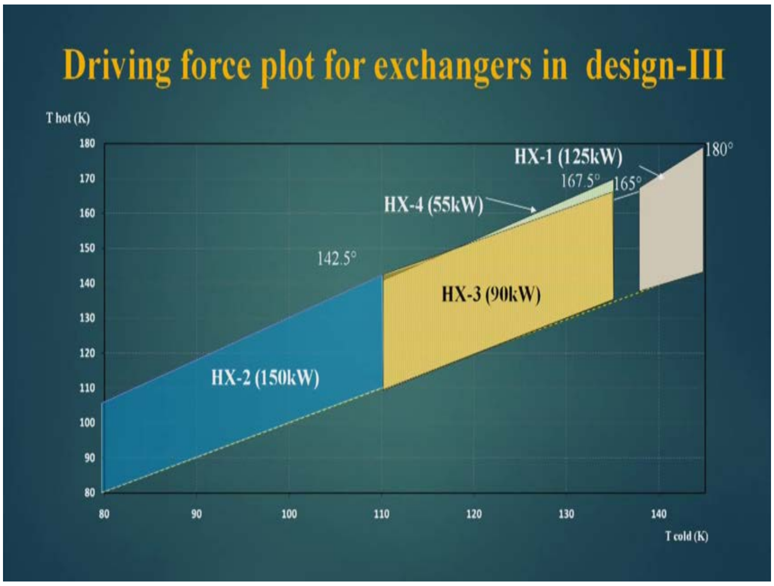

So, when we fold this, then we find this is h x 1 which has got 100 twenty 5 kilo watt it is utilizing the driving force to the fullest extent this is also which is h x 2 100 50 kilo watt this is also utilizing it very nicely to the fullest extent the heat exchanger number 3 which is 90 kilo watt this is also utilizing it to the fullest extent and this is heat exchanger number 4 which is 50 5 kilo watt which is also utilizing the available driving force very nicely and little bit it exits.

so what we find that the design three is in a position to utilize the driving force in the best manner in comparison to the design two and design one though it has got 4 heat exchangers, but its cost on its area 100 meter square only that is the minimum area so if we compare this designs design two has got 2 heat exchangers design one has got 2 heat exchanger design 4 has got 4 heat exchangers but the area is less.

So, there is a trade of finally, design one design two and design three. Out of these 3, we have to select 1 design based on the tact total annual cost, but what conclusion it makes is that if the heat exchangers, which are present in the HEN or utilizing the natural driving force, which is available to it, this natural driving force can be seen through a driving force plot or it can be seen in a composite hot and composite cold curve. So, if this driving force or utilize to fullest extent, we can expect that the area of the heat exchanger network will be minimum and will be almost equal to the targeted area.

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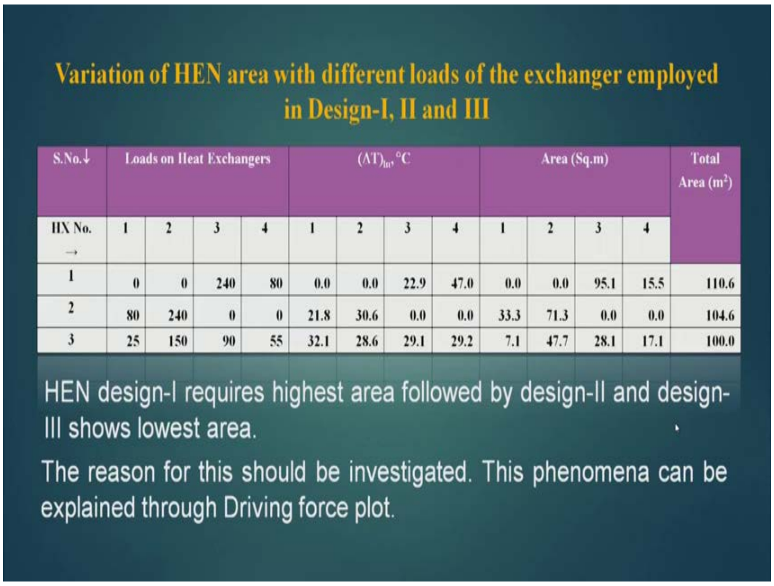
Variation of HEN area with different loads of the exchanger employed in Design-I, II and III

S.No.↓	Loads on Heat Exchangers				$(\Delta T)_{lm}$, °C				Area (Sq.m)				Total Area (m^2)
HX No. →	1	2	3	4	1	2	3	4	1	2	3	4	
1	0	0	240	80	0.0	0.0	22.9	47.0	0.0	0.0	95.1	15.5	110.6
2	80	240	0	0	21.8	30.6	0.0	0.0	33.3	71.3	0.0	0.0	104.6
3	25	150	90	55	32.1	28.6	29.1	29.2	7.1	47.7	28.1	17.1	100.0

HEN design-I requires highest area followed by design-II and design-III shows lowest area.

The reason for this should be investigated. This phenomena can be explained through Driving force plot.

So, again we see this table and we have explained why the heat exchanger 1 has got maximum area. Heat exchanger 2 has got area in between these 2 extremes and heat exchanger 3 has got minimum area.

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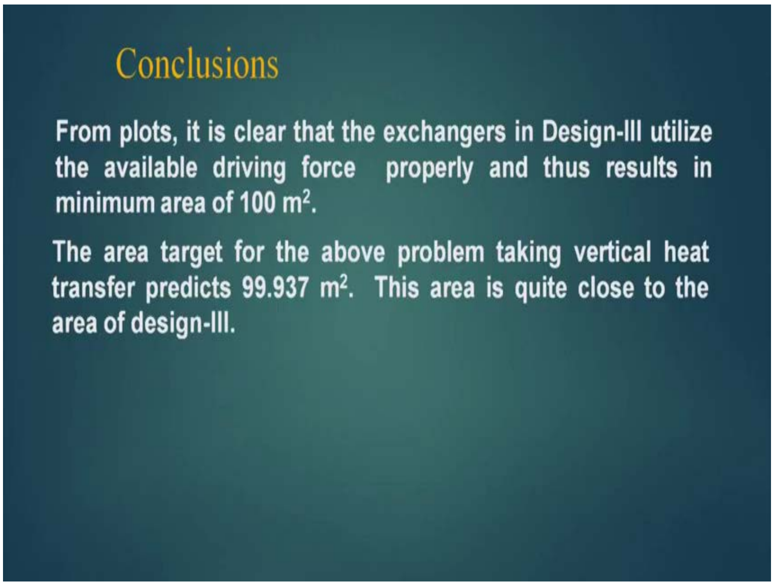

Now, the conclusions for this part is from plots, it is clear that the heat exchanger in design three utilizes the available driving force properly and thus results in minimum area of 100 meter . The area target for the above problem taking vertical heat transfer predicts 99.937 meter square area. So, it is almost equal to 100 meter square area. This area is close to the area of design three.

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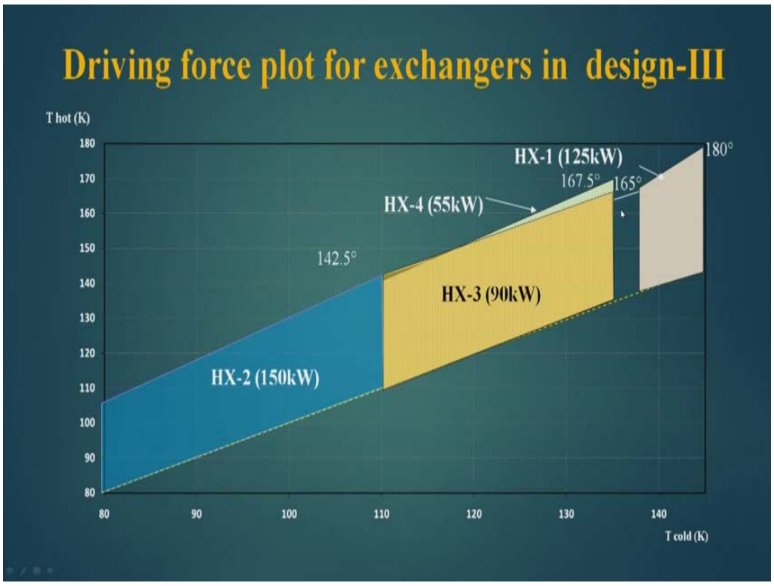

Now, if you remember design three, we have seen that it was not able to utilize this driving force; otherwise its area should be almost near. This is near to the targeted area may be match to this the area.

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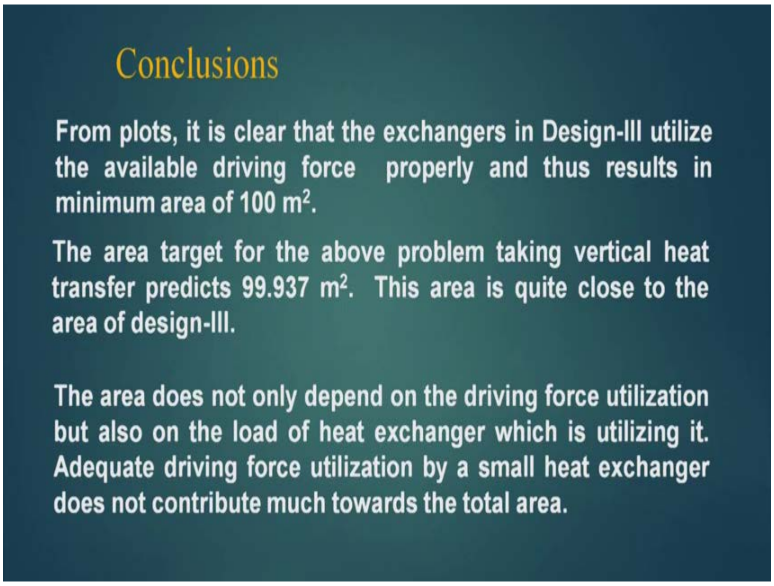

The area does not only depend on the driving force utilization, but also on the load of the heat exchanger, which is utilizing it. So, there are 2 important factors for the area that how much the naturally available driving force is utilized by a heat exchanger plus what is the load of the heat exchanger is utilizing. This adequate driving force utilization by a small heat exchanger does not contribute much towards the total area. We have seen that when in the design one is smaller, heat exchanger utilize the driving force nicely or it is over utilized it, but the bigger heat exchanger did not utilize it properly. Hence, the area of that HEN, which was design one increased.

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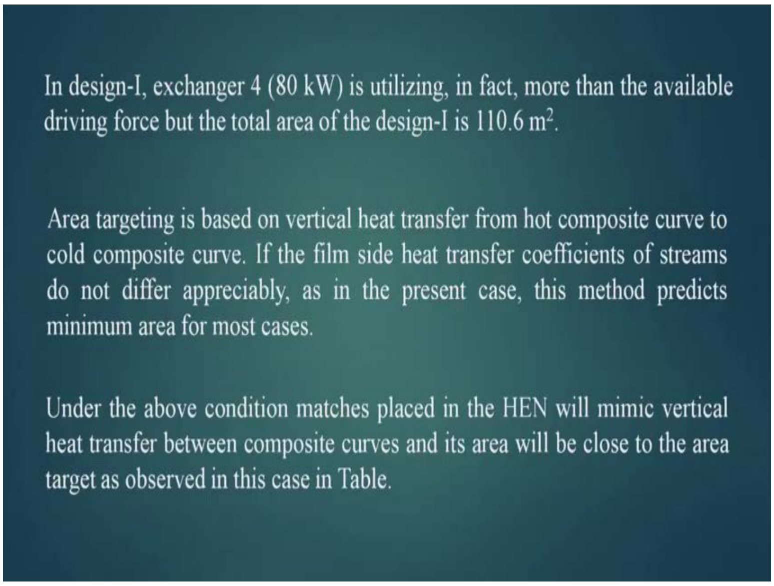

In design one, heat exchanger number 4, which is 80 kilowatt, is utilizing, in fact, more than the available driving force, but the total area of the heat exchanger is 110.6 meter square. Only due to this because the heat exchanger, the second heat exchanger which was got a capacity of 240 kilo watt was not utilizing the available driving force properly, area targeting is based on vertical heat transfer from hot composite curve to the cold composite curve.

If the film side heat transfer coefficient of streams does not differ appreciably, as in the present case, this method predicts minimum area for most cases. But, this will not be true if the overall of the film side heat transfer coefficient of streams differ considered we say more than 10 percent. Under the above conditions, matches placed in the HEN will mimic vertical heat transfer between composite curves and the area will be close to the area target as observed in this case in the table.

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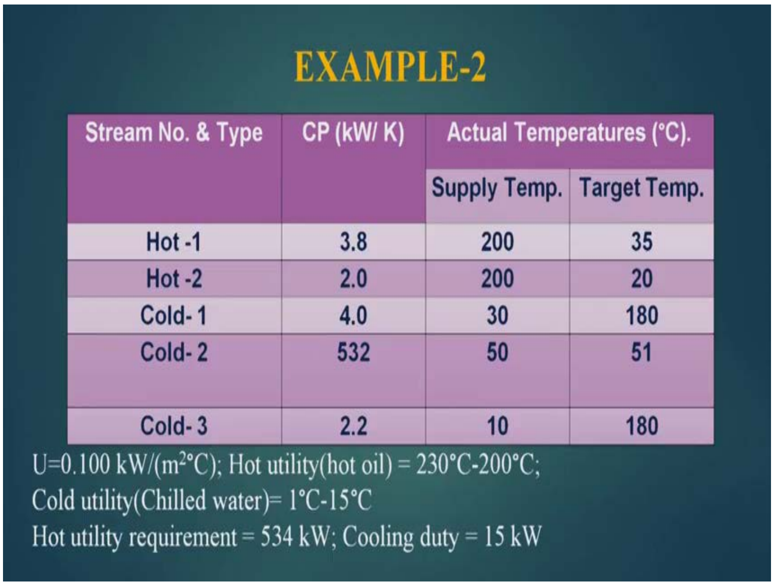

Now, we go for example 2. For this example also, we will have different heat exchanger networks designed. We will also see that though we have the C P ratio rules, even then due to the utilization of driving force by different heat exchangers, the area is different for this purpose. What we are taking U is equal to 0.1 kilo watt per meter square centigrade, hot utility is 230 degree centigrade to 200 degree centigrade; cold utility is 1 degree to 15 degree centigrade. Now, if we do the PTA of this stream table, then hot utility requirement is 534 kilo watt and cold cooling duty is 15 kilo watt.

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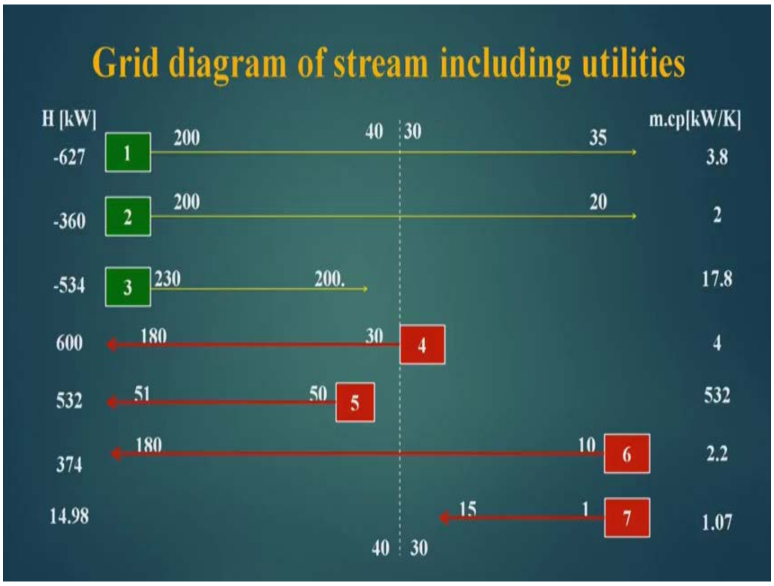

Grid diagram for the including utilities, so this was the grid diagram. The pinch is 30, 40, the delta T being 10 degree, the m c p values.

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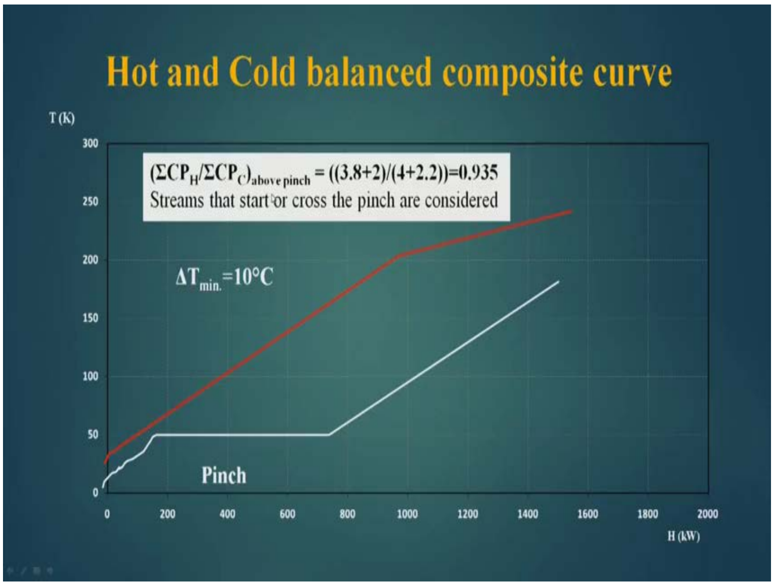

Now, if we see the composite curve, this composite curve looks like this. These are the delta Ts is driving forces, which are available natural driving forces are available to the different streams. Now, if I consider vertical heat transfer the stream, which are available here hot stream as a delta T available with the cold stream is this much. So, this also shows the driving force available between hot and cold stream. This is a hot and cold balanced composite curve that means the hot utility and cold utilities are included into this. Now, here the C P ratio is of the pinch.

Now, here I want to clarify that we have taken those streams, which are crossing the pinch for the computation of this those streams, which are not touching the pinch we are not taking. Similarly, in the number of streams criteria, we count those streams, which are crossing the pinch or you are starting from the pinch. We do not consider those streams, which are not touching the pinch or which end before the pinch.

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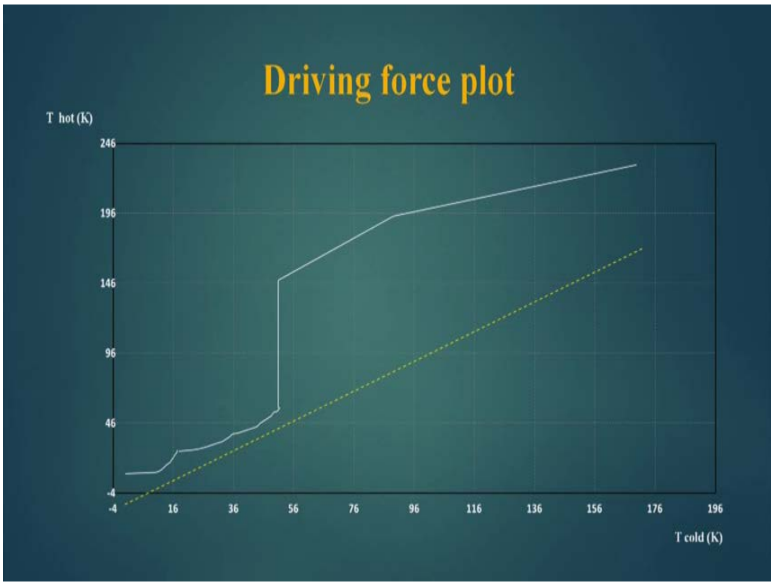

Now, this is the driving force plot of this problem. It is between T cold and T hot. So, these are the driving forces, which are available and the design has to utilize this properly.

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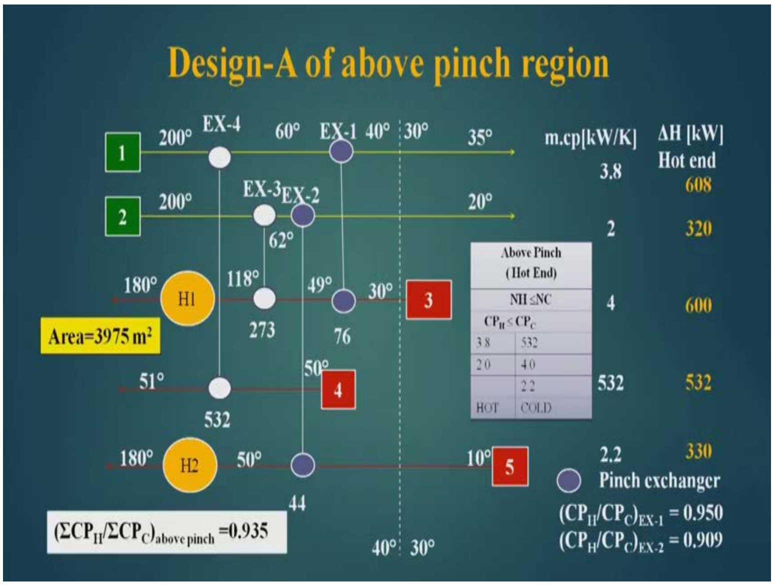

Now, we say design A is taking above the pinch region. This is my C P table, which will be utilizing for the design purpose. Here, we are placing the heat exchangers. Now, these 2 are the pinch heat exchangers called heat exchanger number 1 and heat exchanger number 2. This is a third heat exchanger number 3 and this is fourth heat exchanger heat exchanger number 4 and there are 2 heaters here. Now, if we compute the C P H by C P C ratio of the heat exchanger number 1 and heat exchanger number 2, which are pinch heat exchangers, then the ratio is 0.950 and 0.909. If you see the summation of the C P H by summation of the C P C ratio above the pinch is, this is 0.935.

Now, if we go for the pinch, go for the C P summation of the C P with ratio, and then this value is almost equal to this value meaning that these pinch heat exchangers are utilizing the driving force properly. But, we should see that this pinch heat exchangers of capacity less where as these heat exchangers of capacity more. Now, the area of this heat exchanger network is 3975 meter square that means we have use the C P ratios properly. Then, my design gives me area 3975 meter square. I expect this area to be close to the area target because I have idea to the C P ratio rule. However, we will see these stories differently. Now, if I plot the utilization of available driving force by the heat exchangers of a design A, then this is heat exchanger number 4.

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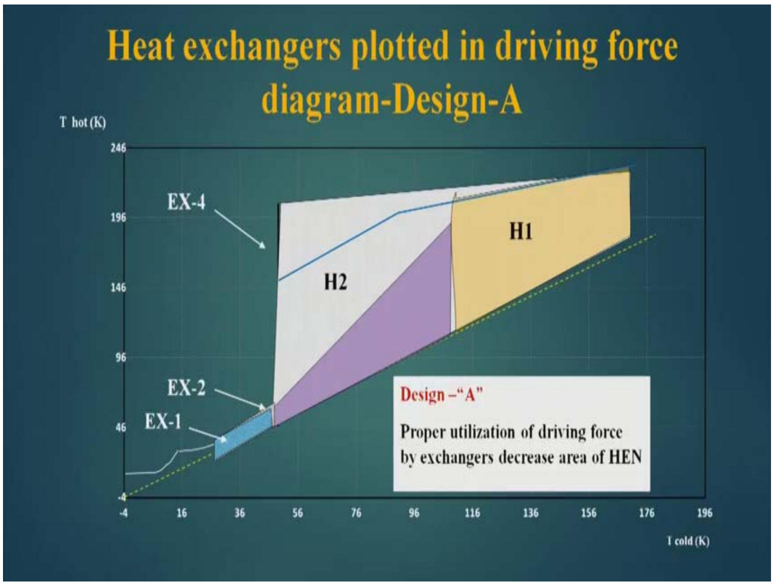

It is nicely utilizing the available driving force or we can say that it is utilizing more. This is the driving force area and we have utilizing more the heat exchanger number. The heater number H 1 is also utilizing the driving force nicely. The H 2 is which is heater is also utilizing the driving force, but not to that extent. It is not fully utilizing the driving force. This E X 2 is utilizing the driving force, which is available in this design. Then, E X 1 is also utilizing the driving force.

Now, design if proper utilization of driving force is taking place by the heat exchangers and that is why the area which we have found is less. When I say less, it is comparison to the other design, which I am going to explain you.

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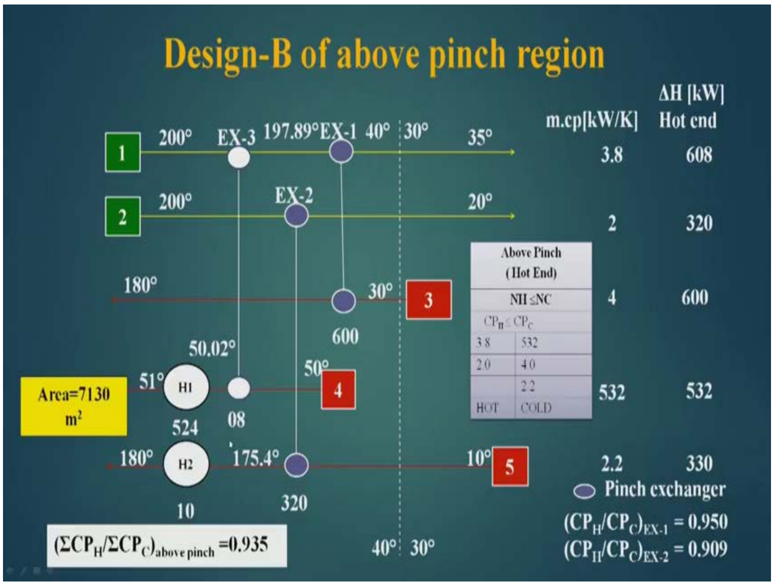

Now, design B, if we do which is also a above the pinch, so here also, if I see the pinch heat exchangers C P ratio, they are quite close to the summation of C P ratio above the pinch. They are very quite close to it, but the area is 7130, which is almost double the area of the previous example that is design A.

Now, if we want to know why this happen, we go for the C P ratio. We have matching is there cp ratio matching of the pinch heat exchangers, but why it has increased so much? So, the answer is, probable answer is here we see the pinch heat exchangers are higher capacities and they are operating at lower delta T values, where as the other heat exchangers at E X 3 has got a very low value.

Now, let us see the driving force plot.

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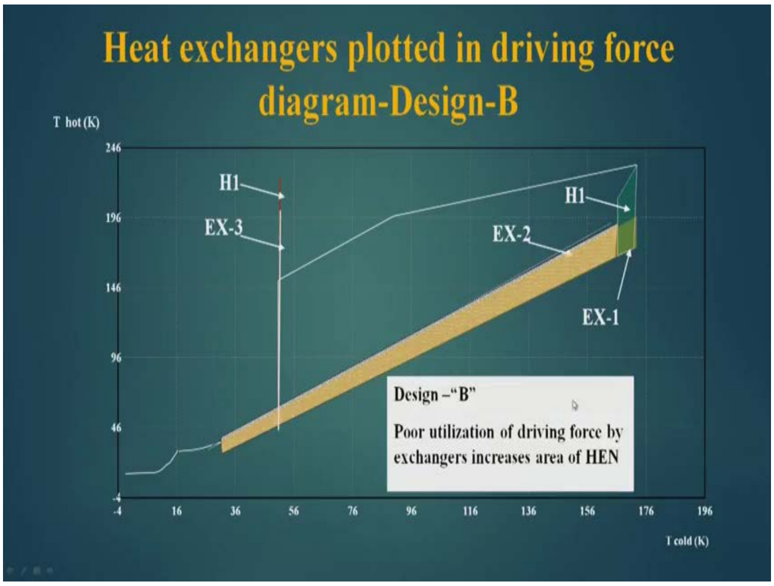

Now, this is the available driving force for plot. For us, this is the exchanger number 2 utilizing, it is not utilizing to the fullest extent, and then exchanger number heater is not utilizing to the fullest extent. This is exchanger number 1. It is not utilizing to the fullest extent, the available driving force and this is the heater 1, 1 of them heater 2. This is exchanger number 3. So, what we see that the pure utilization of the driving force by the exchangers increase the area of HEN because this much area of the heat exchanger network, this much driving force of the heat exchanger network is not utilized properly.

Hence, the HEN area has increased and it has almost been double the area. So, what we saw that even if we utilize the C P ratio rules in the design, there are 2 factors, which come whether the heat exchangers available are utilizing the available driving force properly. The second is that is the bigger heat exchangers are not utilizing the available driving force properly that bigger capacity heat exchangers. Then, the area will increase and it may be 2 folds as we have seen in the design A and design B. So, these are the references.

Thank you.