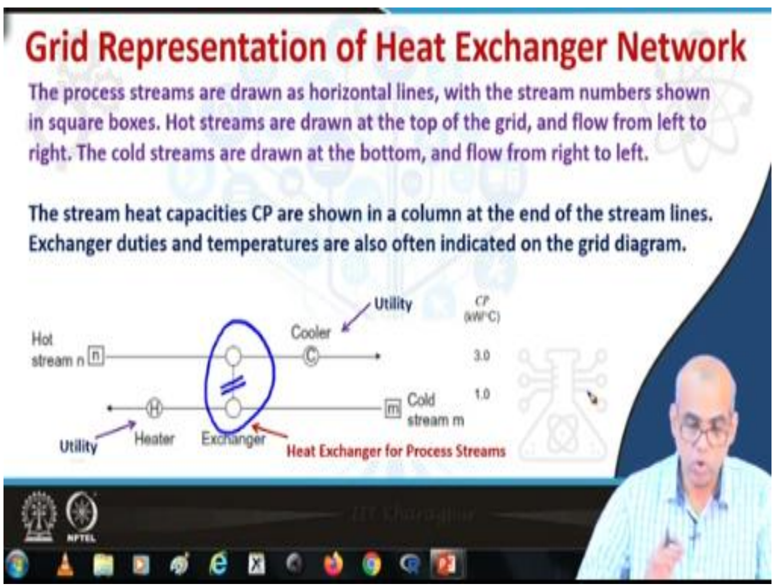
Plant Design and Economics
Prof. Debasis Sarkar
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture No -50
Heat Exchanger Network Design

Welcome to lecture 50 of plant design and economics. In this last lecture of module 10 will take a very simple example of heat exchanger networks synthesis. So we will take a case where we have two hot streams and two cold streams. So let us go through a very basic example of heat exchanger network design.

(Refer Slide Time: 00:42)

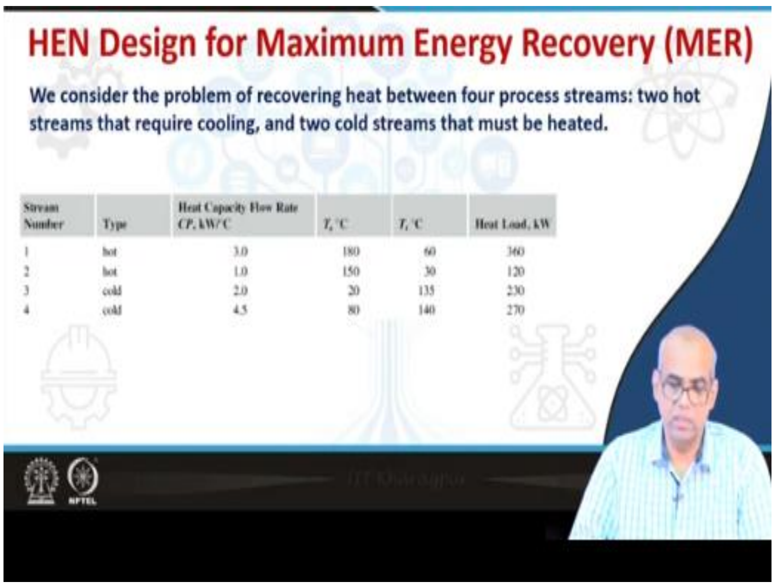


First, let us talk about grid representation. How do you represent this process streams? How do you represent heaters coolers? How do you represent the exchanger that will allow heat recovery exchanges of heat between two process streams? The process streams are drawn as horizontal lines with the stream numbers zone in square boxes. Hot streams are drawn at the top of the grid and flow from left to right.

The cold streams are drawn at the bottom of the grid and flow from right to left. So this is cold stream and this is hot stream. The stream heat capacities that means; CP values are also shown in a column at the end of the stream lines. Exchanger duties and the temperatures are also often indicated on the grid diagram. So heater and cooler which are hot utilities are cold utilities are represented by circles like this.

Note that cooler is represented by C, letter C within this circle and the heater is represented by a circle with letter H in it. These two circles join by a vertical line represent the heat exchanger for process streams. For example, it may be a salient heat exchanger through which this hot stream and cold steam are passing. So this is a typical grid representation that we will use for this heat exchanger network synthesis.

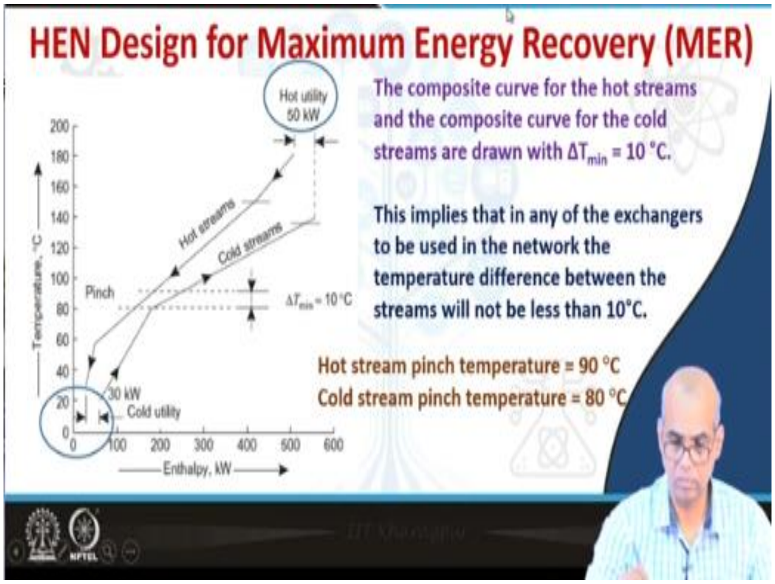
(Refer Slide Time: 03:30)



So let us consider the problem of recovering heat between four process teams where there are two hot streams and two cold streams. So all the target temperatures and the supply temperatures the heat capacity flow rates heat loads all are given. Note that this heat load, this is obtained as difference of supply temperature and target temperature multiplied by the heat capacity flow rate. For example for this particular case but the first stream, which is hot stream 180 - 60 is 120 multiplied by 3 is 360.

So the data about the streams are given. We need to design a heat exchanger network. So first we have to have a basis for design. So we are going to design a heat exchanger network for maximum energy recovery. This is also same as saying we want to make use of minimum utility. So, maximum energy recovery will correspond to minimum uses of hot utility minimum uses of cold utility. So that is the basis for design of current this heat exchanger network.

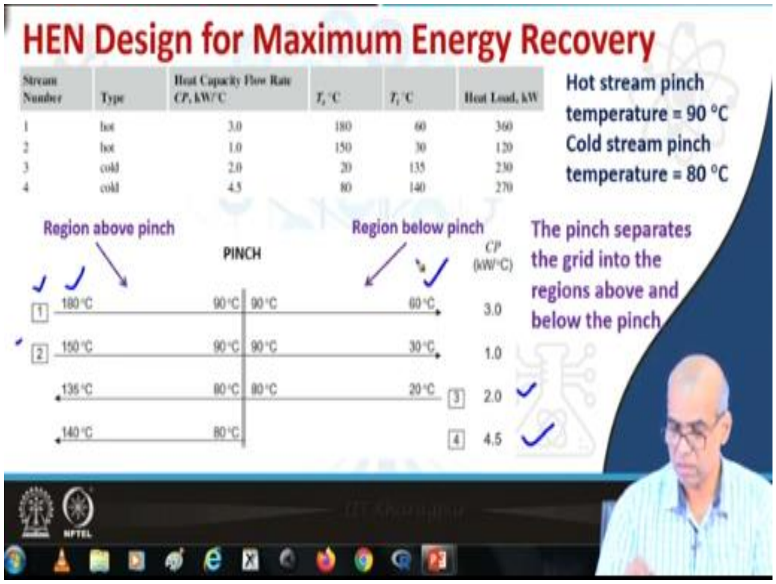
(Refer Slide Time: 05:26)



Now if we consider this data and analyze this using composite curves or using the problem table algorithm for a given delta T minimum, we can obtain the hot utility target and cold utility target as well as the pinch temperatures. For example, what is shown on the figure is the hot composite curve and the cold composite curve and you see that hot utility target is 50 kilowatt and cold utility target is 30 kilowatt for a given delta T minimum of 10 degree Celsius.

So this statement is very important this for these values of hot utility target and cold utility target is valid for the given value of minimum temperature difference delta T minimum. So at this relative position of these two composite curves the vertical distance between these two curves is delta T minimum equal to 10 degree Celsius, so this represents pinch. So we have the hot pinch temperature as 90 degree Celsius. And the cold pinch temperature as 80 degrees Celsius. So, 80 degree Celsius; as cold pinch temperature and 90 degree Celsius as hot pinch temperature.

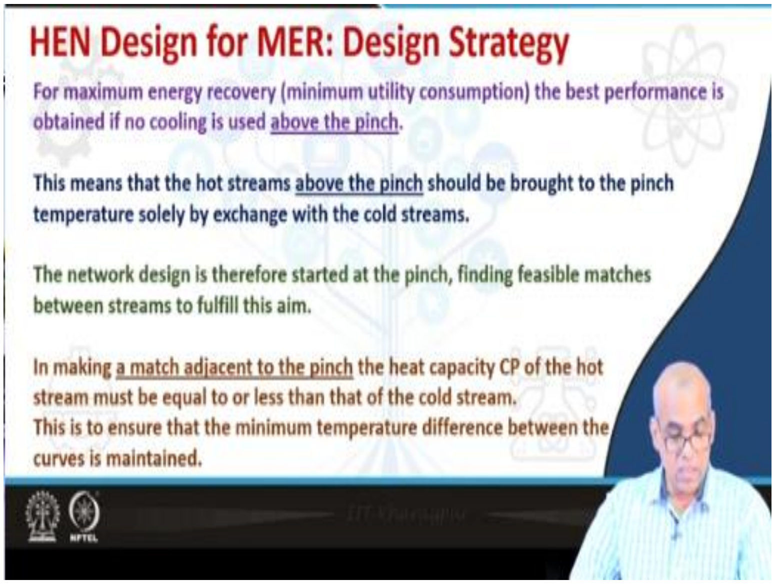
(Refer Slide Time: 07:27)



Now let us look at the grid representation. So the hot streams are towards the above the grid towards the top of the grid and the cold streams are towards the bottom of the grid. Note that the hot stream pinch temperature 90 degrees Celsius and the cold stream to pinch temperature 80 degrees Celsius. This vertical line represents the pinch. So the pinch separates the grid into two regions, region above pinch and region below pinch.

So you have region above pinch and you have region below pinch. Note for all streams, the numbers are given. 1 and 2 are hot streams, 3 and 4 are cold streams. For each stream the supply temperature and the target temperature indicated pinch temperature, of course indicated the CP values are also indicated.

(Refer Slide Time: 09:27)



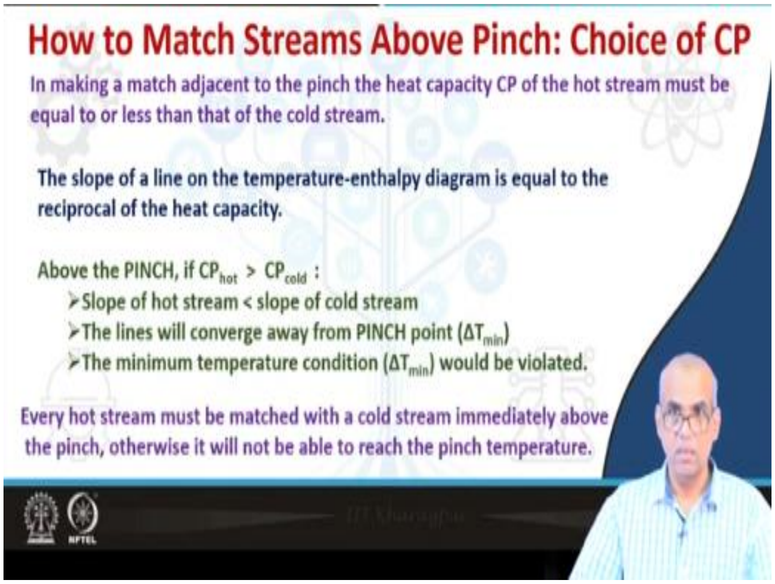
Now, what should be the design strategy for our heat exchanger network such that we obtain high heat exchanger network, which will ensure maximum energy recovery. For maximum energy recovery or synonymously minimum utility consumption, the best performance will be obtained when we do not use any cooling above the pinch. So now let us remember the golden rules for pinch analysis. Above the pinch use only hot utility, below the pinch use only cold utility and avoid the transfer across the pinch.

So maximum energy recovery the base performance is obtained if no cooling is used above the pinch, so what does it mean? This means that the hot streams above the pinch will be brought down to the pinch temperature only by the heat exchange with the cold streams. So the network design will start at the pinch finding feasible matches between hot streams and cold streams, such that this same is fulfilled.

So you have to find feasible matches of hot stream and cold streams such that we can bring down the temperatures of the hot streams to the pinch up only by the exchange of the cold streams above the pinch point. In making a match adjacent to the pinch the heat capacity CP value of the hot stream must be equal to or less than the CP value of the cold streams. I repeat in making a match adjacent to the pinch the heat capacity that is CP value of the hot stream must be equal to or less than CP value of the coal stream.

This ensures that minimum temperature difference between the curves is maintained. Let us now try to understand this point more elaborately.

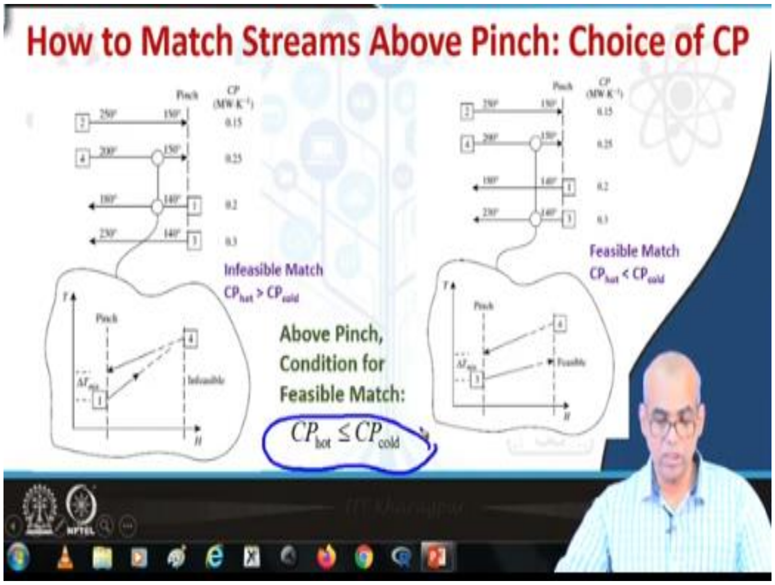
(Refer Slide Time: 12:13)



We know that the slope of a line on the temperature enthalpy diagram is equal to reciprocal of the CP value. So, above the page if I have the CP value of hot stream is greater than CP value of a cold stream, it means that slope of the hot stream is less than the slope of the cold stream because the slope is 1 by CP. So, if CP hot stream is greater than CP cold stream the slope of hot stream is less than slope of cold stream.

So when this happens, these lines will tend to converge away from the pinch point that is delta T minimum point. And then if that happens; the minimum temperature condition will be violated. Remember every hot stream must be matched with the cold stream immediately above the pinch. Otherwise, it will not be able to reach the pinched temperature.

(Refer Slide Time: 13:23)



Now, let us look at this schematic to understand the choice of the CP values. So you see the grid portion for above the pinch region. No, so what we are trying to do here is we are trying to match stream 4 with stream 1. Note that stream 4 is a hot stream and stream 1 is a cold stream. The hot stream 4 has CP value greater than the CP value of the cold stream. So CP hot is greater than CP cold.

So it means that slow of the hot stream is less than the slope of the cold stream and even now see that there converging here, violating the delta T minimum condition, so this is infeasible match. Now, let us consider the reverse situation, where CP hot is less than CP cold and this is happens when I want to match the hot stream 4 with the cold stream 3. So hot stream 4 has CP value less than the cold stream, number 3 is CP value 0.25 versus 0.3.

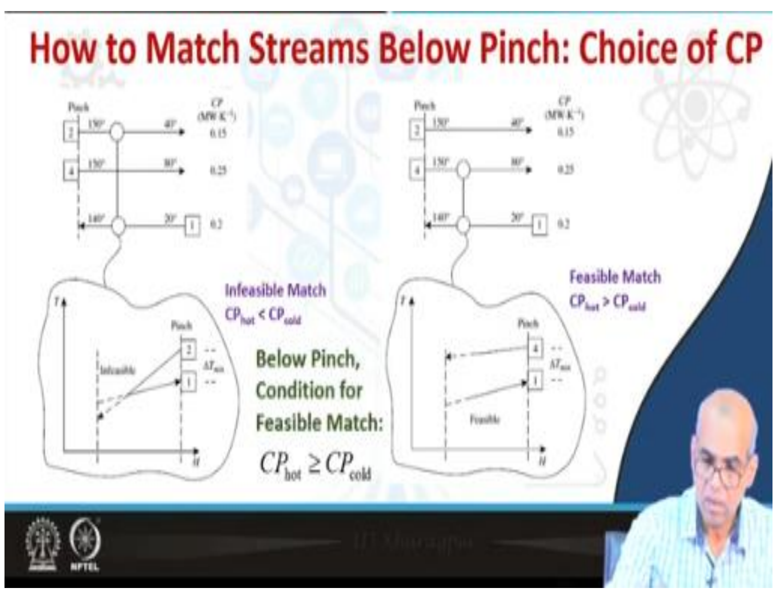
So CP hot is less than CP cold. So the slope of the hot stream is greater than the slope of the cold stream. Now, you see that there is no scope of converging these two streams to a point less than delta T minimum value. The delta T minimum is maintained at the pinch. As you go away from the pinch, they are diverging only, so this is a feasible match. So, the condition that we now set is that above pinch the condition for feasible match is given by CP hot should be less or equal to CP cold.

So above the pinch the condition for feasible matches CP value for the hot stream must be less or equal to CP value for the cold stream.

(Refer Slide Time: 16:44)

Now for the region below the pinch will have the same consideration. Here in the region below the pinch our aim will be to bring the cold streams to the pinch temperature by exchange with hot streams and here the criterion will be the CP value of the hot stream should be greater or equal to CP value of the cold streams that will give the feasible match. It is by the same consideration that we did for matching streams in the region above the pinch. Here also every cold stream must be matched with the hot stream immediately below the pinch.

(Refer Slide Time: 17:29)

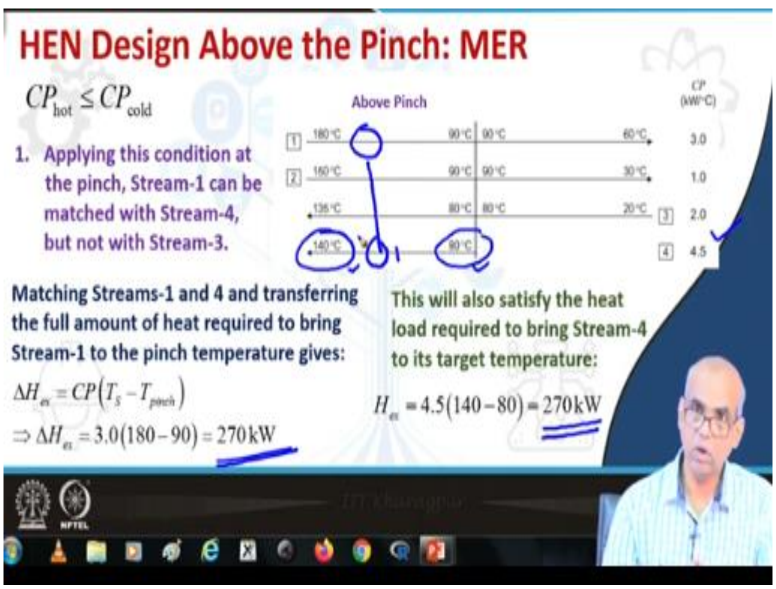


So this schematic will again explain why the CP hot should be greater equal to CP cold. So again, we consider part of the grip below the pinch region. So let us consider the matching of stream 2 with stream 1. Note that stream 2 is a hot stream with capacity of CP value 0.15 and stream 1 is the cold stream with CP value 0.2, so CP hot is less than CP cold. In other words, the slope of the hot stream is greater than the slope of the cold stream.

Now you see that they lead to infeasible match because of the violation of the delta T minimum, they cross at this point. Now let us consider the matching of stream 4 with stream 1. Stream 4 is another hot stream with CP value 0.25 and stream 1 is the cold stream with CP value 0.2, so in this case CP hot is greater than CP cold. So the slope of the hot stream is less than the slope of the cold stream and we see that this particular match is feasible, so this is the set delta T minimum value and the diverge.

So they are not going to violate delta minimum, they are not going to you know, cross anywhere or converge. So the condition for feasible match in the region below the pinch is CP value of the hot stream must be greater or equal to CP value of the cold stream. So CP hot should be greater or equal to CP cold.

(Refer Slide Time: 20:35)



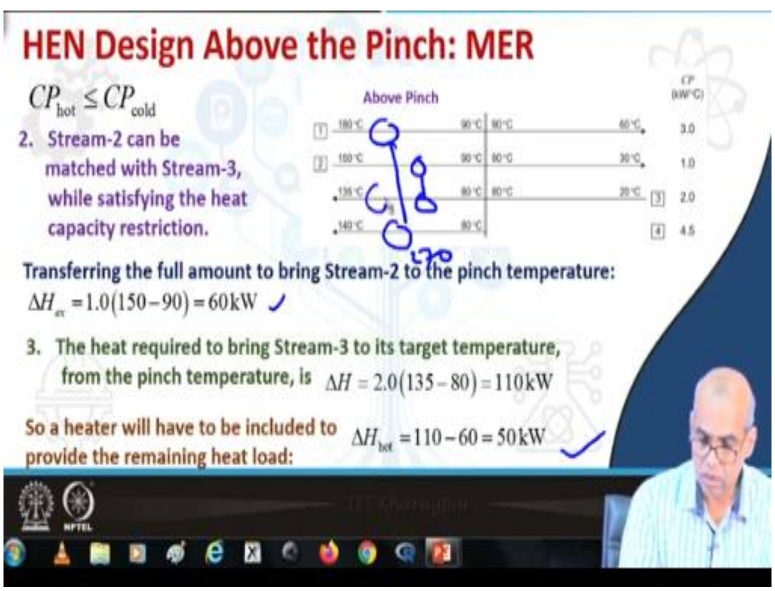
Now let us start designing the heat exchanger network starting with the region above the pinch. We have to remember here that for feasible matches of hot stream and cold stream the condition that must be made is CP value of hot stream is less or equal to CP value of the cold streams, so now when I apply this condition at the pinch, we see that the stream 1 with CP value 3 can be matched only with stream 4, which has CP value 4.5.

So 3 is less than 4.5 but it cannot be matched stream 1 cannot be matched with the other cold stream 3 because it has a CP value of 2 and CP hot cannot be greater than CP cold above pinch. So, I had to match stream 1 with stream 4. So matching stream 1 and 4 let us transfer the full amount of heat required to bring stream 1 to the pinch temperature, which you can obtain as H is equal to CP into delta T. So that gives us 3 multiplied by 180 -90 so, this is 270 kilowatt.

So, this is the full amount of heat required to bring stream 1 to the pinched temperature. This will also satisfy the heat load required to bring stream 4 to it is target temperature. What is that? Stream 4 target temperature is 140 degree Celsius. Note the same 4 is a cold stream which must be heated from 80 degree Celsius to 140 degree Celsius. So what is the heat load? It has CP value of 4.5, so 4.5 multiplied by 140 - 80 that gives 270 kilowatt.

So this is same as the heat that was obtained from stream 1. So by matching stream 1 and stream 4 these two conditions are made.

(Refer Slide Time: 23:42)



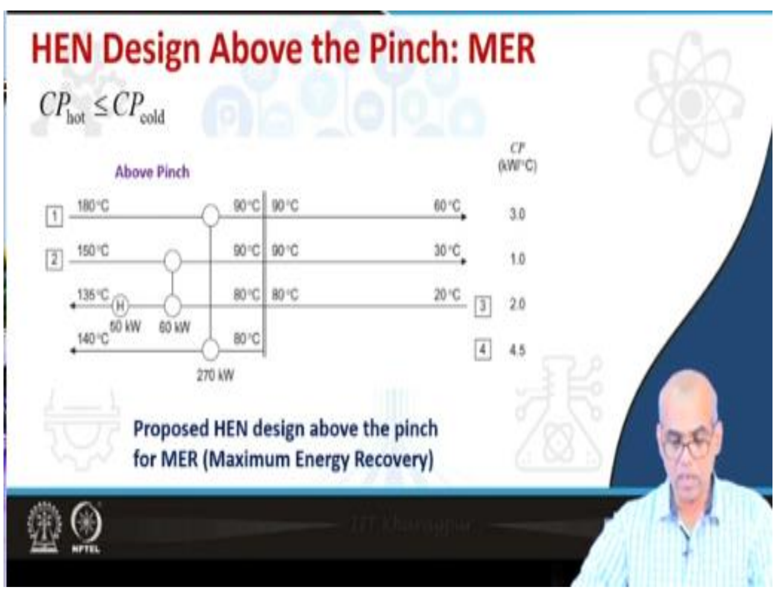
So now let us look at stream 2, so stream 2 is another hot stream. So, which we can match with stream 3 because stream 2 has CP value 1, which is less than the CP value of stream 3. So stream

2 can be matched with stream 3 and this is satisfying the CP hot lesser equal to CP cold feasibility condition. Now transfer the full amount to bring stream to the pinch temperature. Calculate the value delta H equal to 1 multiplied by 150 - 90, which gives me 60 kilowatt.

So 60 kilowatt will be available from the hot stream number 2 when it is brought down to temperature 90 degree Celsius from 150. So, what is the heat required to bring steam 3 to its target temperature? That means from 80 degree Celsius to 135 degrees Celsius, so to obtain that 2 multiplied by 135 – 80, so that gives me 110 kilowatt. So, 60 was obtained by pairing stream 2 and stream 3, we obtained 60 kilowatt from stream number 2, but stream number 3 requires 110 kilowatt to attain its target temperature.

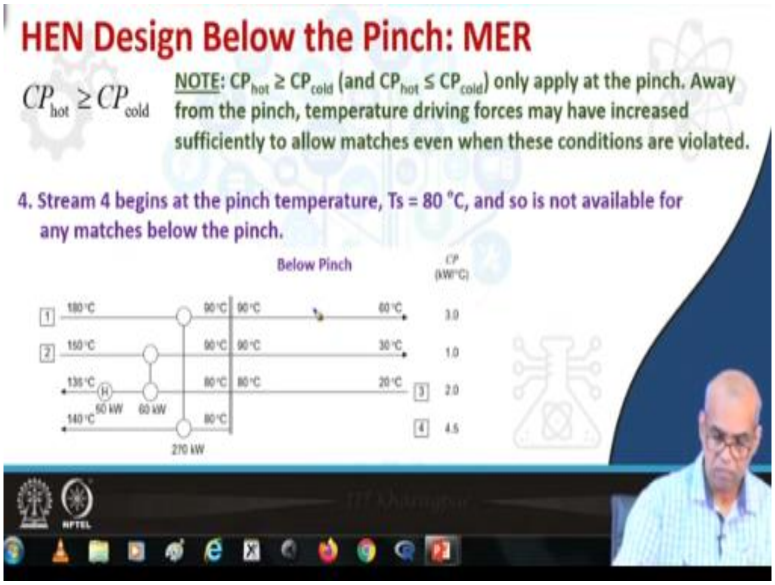
So the remaining heat 110 - 60 that is 50 kilowatt must be provided by hot utility. So a heater will be required to provide the remaining heat load of 110 - 60 equal to 50 kilowatt. So what we did is we first paired 1 and 4 and got to 70 and then 2 and 3 which gave 60 kilowatt. But then it was not enough for stream 3, so that required a heater. So this completes the design for the region above the pinch.

(Refer Slide Time: 27:05)



So now you see the proposed heat exchanger network design for the region above the pinch for maximum energy recovery.

(Refer Slide Time: 27:17)



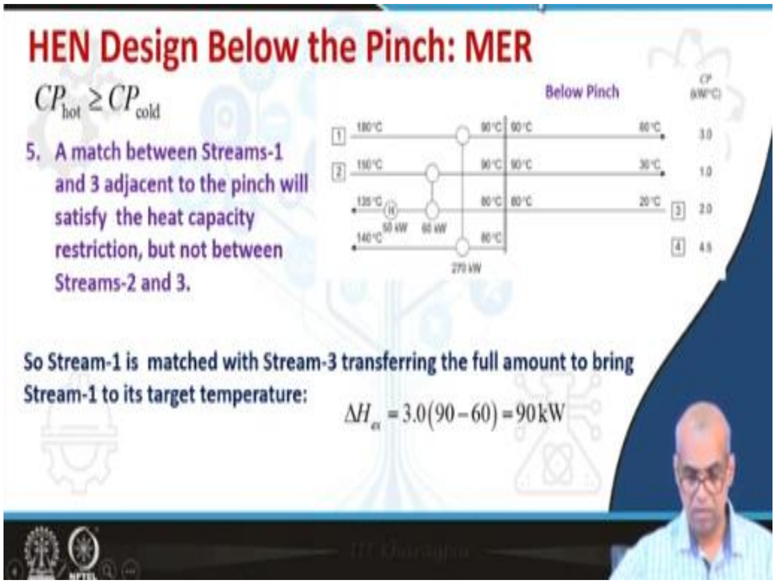
Now, let us start designing for the region below the pinch. In this region the criterion on CP is the CP values of hot stream must be greater or equal to CP values of the cold stream. Now a clarification is required at this stage, note that the criterion such as CP hot stream is greater equal to CP cold stream in the region below the pinch and CP for hot stream lesser equal to CP for cold stream in the region above the pinch, these inequalities is applicable only adjacent to the pinch.

So when you are matching streams adjacent to the pinch these criterions must be fulfilled. Away from the pinch the temperature driving forces may have increased sufficiently to allow matches even when these conditions are violated. Of course, we must find out the temperatures finally to make sure that there is no violation of delta T minimum. But the conditions on CP values are strictly applicable adjacent to the pinch.

So for stream matching adjacent to the pinch, we must make sure that these restrictions on CP values of hot stream and cold streams are obeyed. Away from pinch perhaps temperatures have increased sufficiently and that increase in temperature will allow the matches between two streams which perhaps violate such conditions. So for the design below the pinch we have CP of hot streams greater or equal to CP of cold streams for matches adjacent to the pinch.

The same is true for designing for the region above the pinch as well. Now, let us look at the grid indicating the network. This is the region below the pinch. We see that stream number 4 begins at the pinch temperature of 80 degrees Celsius and it is not available for any stream matching in the region below the pinch. So for all practical purposes we are left with 3 streams for the region below the pinch, 2 hot streams and 1 cold stream.

(Refer Slide Time: 30:41)

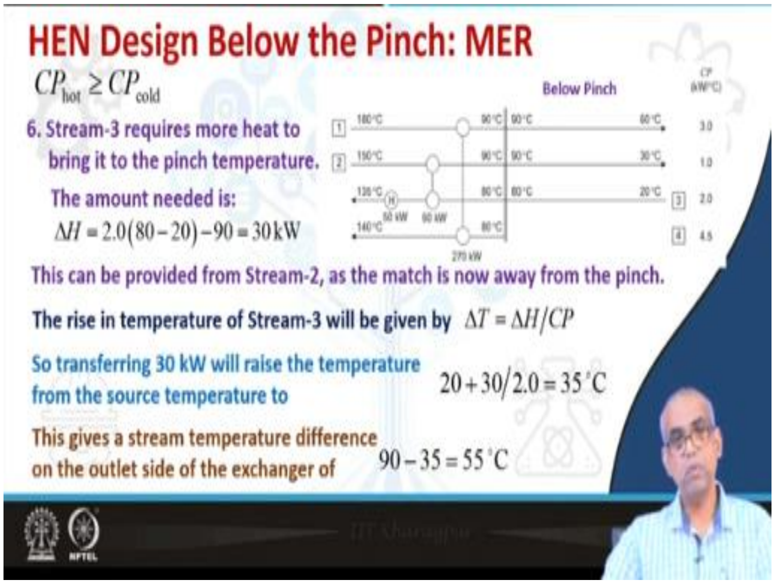


Now, how do I do the matching? So let us look at the CP values. Is a match between streams 1 and stream 3 possible? It is possible. A match between stream 1 and stream 3 adjacent to the pinch is possible, because 1 has CP value 3 and the stream 3 CP value 2, so CP value of hot stream 1 is greater than the CP value of cold stream 3. So a match between stream 1 and stream 3 adjacent to the pinch is possible if satisfies the capacity restriction.

But what about matching between stream 2 and stream 3? It is not possible, because of the capacity restriction so the matching adjacent to pinch is not possible, so in match stream 1 with stream 3. So when I match stream 1 and stream 3, if I transfer the full amount of heat to bring the stream 1 to its target temperature, what is the del H value? That is 90 - 60 multiplied by 3, so that gives me 90 kilowatt of heat.

So bringing the stream 1 from temperature 90 degree Celsius to target temperature 60 degree Celsius gives me 90 kilowatt of heat.

(Refer Slide Time: 32:34)



Now this stream 3 gets this 90 kilowatt from stream 1. So this represents the heat exchange between this two process streams, stream 1 and stream 3, But how much? Stream 3 will require for increase in the temperature from 20 degrees Celsius to its pinch temperature 80 degrees Celsius. It will require 80 - 20 multiplied by 2, which is 120 available from stream 1 is 90. So additional 330 kilowatt heating is required now will supply this heat.

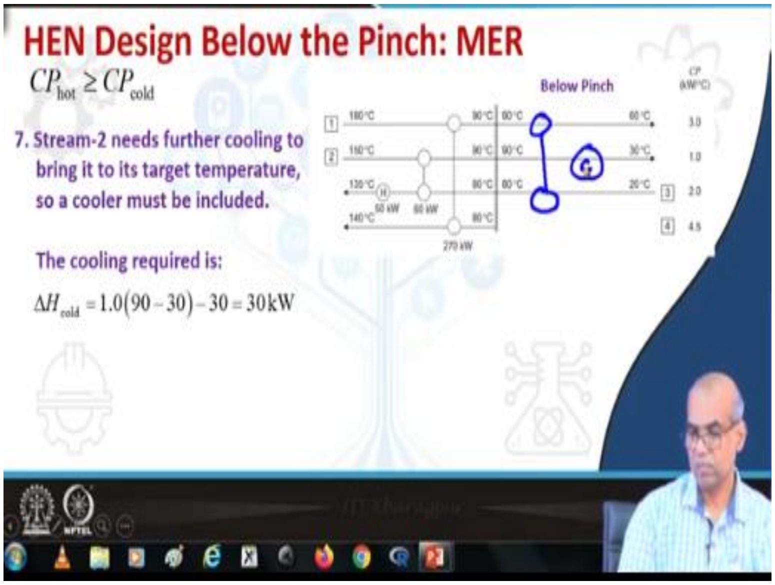
This can be provided by stream 2, note that the CP value of the stream 2 is less than the CP value of stream 3. So the condition CP of hot stream greater equal to CP cold stream is being violated, but this match is now away from the pinch. So this is feasible this match can be feasible, of course, we must find out the temperature and make sure that delta T minimum is not being validated.

So the stream 2 will provide the 30 kilowatt necessary heating to stream 3, so for that the temperature of the stream 3 will increase by what we can find out that delta T equal to delta H by CP. So initially it was 20 degrees Celsius, the temperature this supply temperature of the cold stream number 3 and 30 kilowatt is being supplied by stream number 2. So the temperature will be 20 + 30 by 2 equal to 35 degree Celsius.

So the transfer of 30 kilowatt from stream number 2 to stream number 3 will raise the temperature of stream number 3 from source temperature of 20 degrees Celsius to 35 degree

Celsius. So this will give us stream temperature difference on the outlet side of the exchanger as 90 - 35, which is 55 degrees Celsius. So definitely it is not violating the delta T minimum. So the match is feasible.

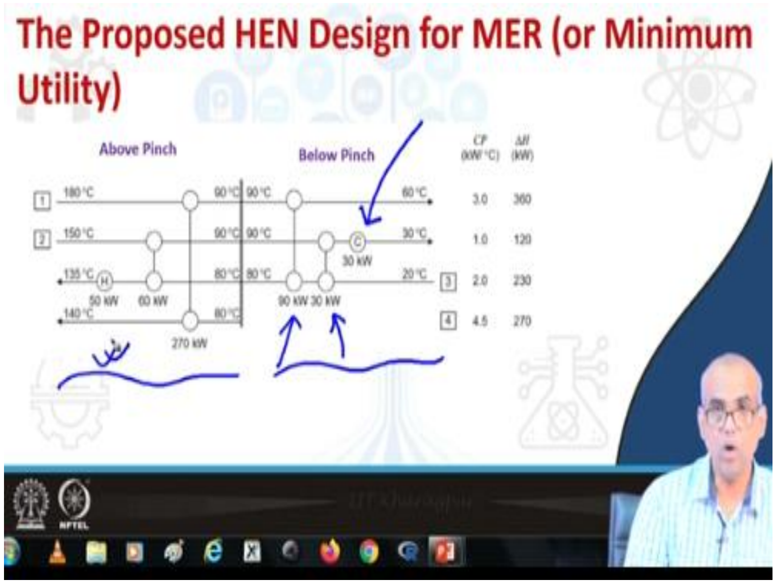
(Refer Slide Time: 35:48)



So; now after removing 30 kilowatt from stream 2. Stream 2 requires further cooling to bring its temperature to the target temperature of 30 degree Celsius. What is the temperature from pinch temperature over 90 degree Celsius to target temperature 30 degree Celsius, it requires 1 multiplied by 90 - 30 is 60. So it has already given 30 kilowatt to stream number 3, so additional 30 kilowatt of removal heat removal or cooling is required on stream number 2.

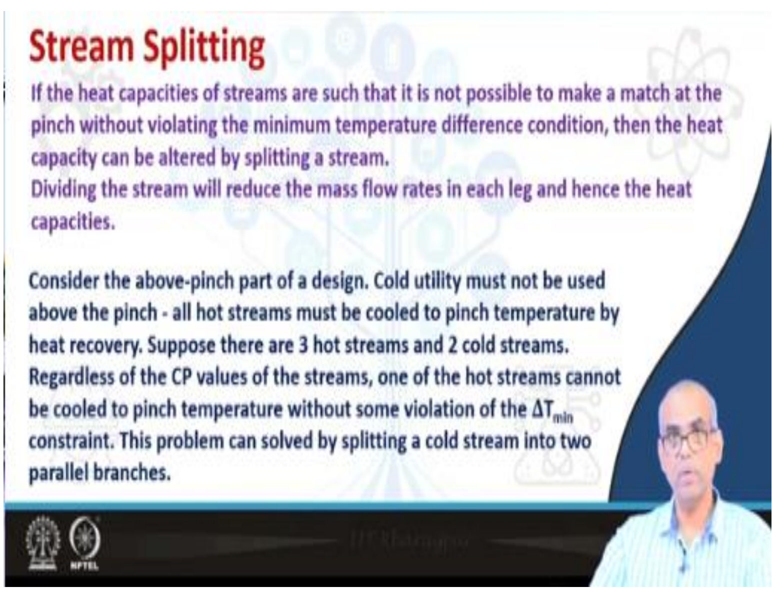
So we will give do that we require a cold utility. So the cold utility on stream number 2 is required and that is to the stream of 30 kilowatt.

(Refer Slide Time: 37:01)



So this becomes the final complete design. This is the above pinch per and this is the below pinch part. So in this below pinch part, you have stream number 1 and 3 paired up. So you obtain 90 kilowatt and then 30 kilowatt is obtained from the stream number 2, but then stream number 2 requires additional cooling by a cooler. So note that only hot utility is used above the pinch only cold utility is used below the pinch.

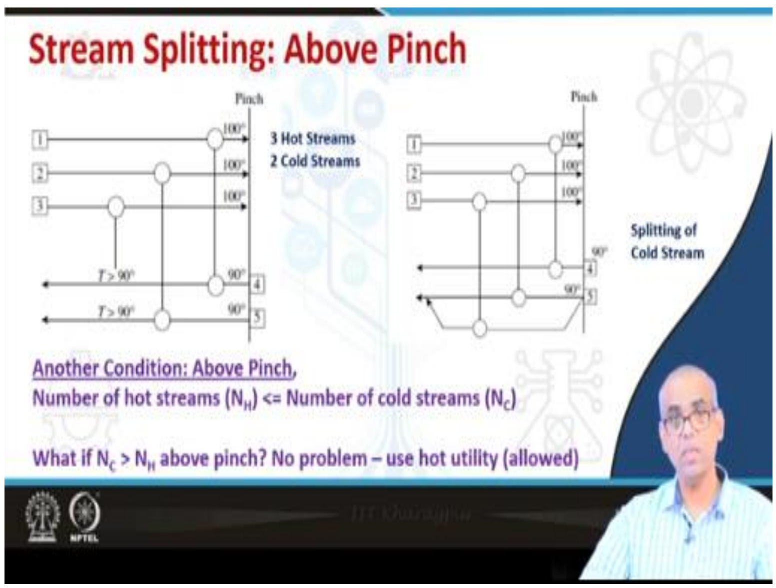
(Refer Slide Time: 37:49)



Now if the heat capacities of streams are such that it is not possible to make a match at the pinch without violating the minimum temperature difference condition, then the heat capacity can be changed by splitting a stream that means a strain can be divided into two parallel streams and by doing that we are basically changing the mass flow rate. So thereby we are changing the heat capacities.

So stream splitting can be necessary when we do not find phase possible match between streams. Consider a case above the pinch. Above the pinch, we must not use cold utility. So, all hot streams must be cool to pinch temperature by heat recovery only. Suppose there are 3 hot streams and there are only 2 cold streams. So regardless of the CP values of the stream, one of the hot streams cannot be cooled to pinch temperature without some violation of delta T minimum. Now this problem we can resolve by splitting a cold stream into two parallel branches as shown here.

(Refer Slide Time: 39:06)

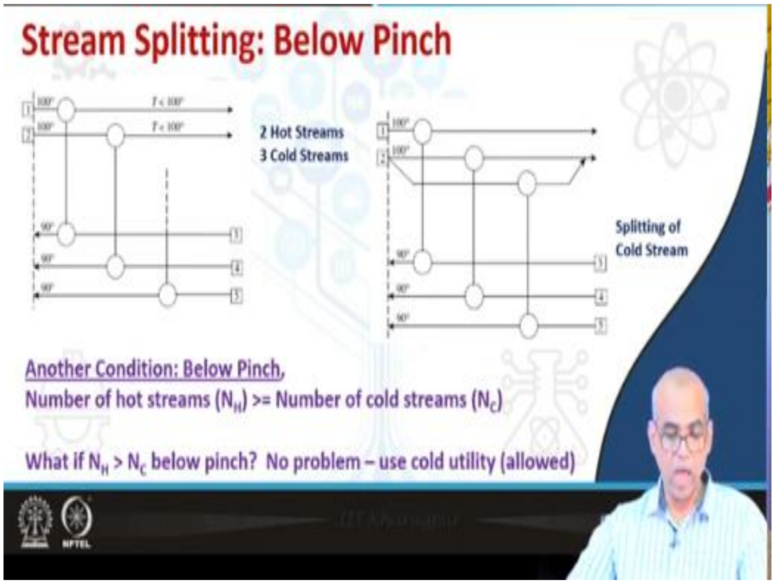


Note here that you have three hot streams and two cold streams. So I can do the feasible matches by splitting one of the cold streams into two parallel branches. So this gives me one additional condition in the region above pinch. Apart from conditions on CP values, the condition is this that number of hot streams must be less or equal to number of cold streams in region above the pinch.

So in the region above the pinch number of hot stream must be less or equal to number of cold streams. What if I have number of cold stream is greater than number of hot stream in the region above the pinch? Note that the condition is number of hot streams should be less or equal to number of cold streams. So number of cold streams if more than number of hot streams, then that is not a problem because you can use hot utility in the region above the pinch.

So, that is not a problem. So cold streams can exceed number of cold streams can exceed number of hot streams in the region above the pinch because you are allowed to use hot utility to cool down the temperature of the cold streams.

(Refer Slide Time: 40:57)



Similarly below the pinch now in this at below the pinch, you are not allowed to use hot stream you are allowed only to use cold stream. So all the hot streams, sorry all the cold streams must be heated up by heat streams only. So all the cold streams must be heated by hot streams only. So in a case if I have say 3 cold streams and 2 hot streams, so I can split one hot stream in two parallel branches for making feasible matches.

So again, I have additional conditions apart from conditions on CP values. So number of hot streams in the region below the pinch must be greater or equal to number of cold streams. Here the number of hot streams must be greater or equal to number of cold streams. You are allowed to use cold utility in the region below the hot stream. So if you have more number hot streams, then cold streams that is not a problem because you can always use cold utility.

(Refer Slide Time: 42:30)

Now a final comment on the heat exchanger network that we design. The heat exchange network we design will give the maximum heat recovery and will therefore give the minimum consumption and cost of the hot and cold utilities because it was designed on the basis of maximum energy recovery which is equivalent to saying minimum consumption about utility minimum consumption of cold utility.

But this is not necessary that this is an optimum design as well. The optimum design will be that which gives the lowest total analyzed cost and the lowest total analyzed cost will depend not only on the cost of utility but also on the capital cost of the system. So the optimum design will be that which gives the lowest total annualized cost taking into account the capital cost of the system, in addition to the utility and other operating cost.

So the number of exchanges in the network the sizes of the exchanges will determine the capital cost and when you want to find out the optimum heat exchange network, we must take into account the capital cost of the exchanger as well as the operating cost and utility cost. With this we conclude our module number 10 here.