Plant Design and Economics
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Lecture No -47
Composite Curves

Welcome to lecture 47 of plant design and economics. In this module we are talking about heat exchanger network synthesis. In our previous lecture, we have talked about a simple problem with just two streams; one hot stream and one cold stream. In today's lecture, we will extend those concepts for a case with multiple streams. We will do this by introducing a concept called composite curves.

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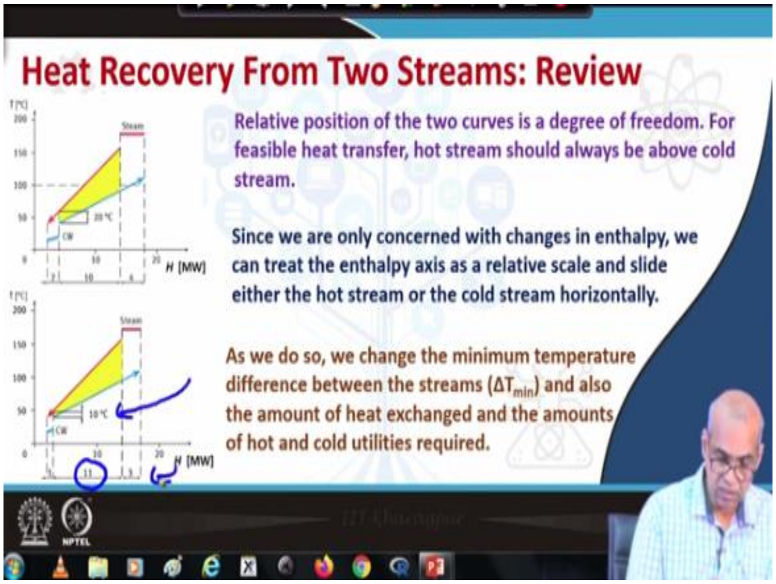

Let us first quickly review what you have learnt for two stream systems. Now look at the temperature enthalpy diagram on which one hot stream and one cold stream we have plotted. The hot streams have been plotted from its supply temperature to target temperature and also the cold streams have been plotted from its supply temperature to its target temperature. We also know that slope of this curve is 1 by CP where CP is the heat capacity flow rate.

It is a product of mass flow rate and specific heat capacity. Now the relative position of this hot stream and the cold stream is a degree of freedom. We know that for feasible heat transfer, the hot stream should always be hotter than the cold stream. So, hot stream will always be above the cold stream. Now on this stage diagram, we are only concerned with the changes in enthalpy. So if that is the case, we can treat the enthalpy excess as the relative scale.

And slide either the hot stream or the cold stream horizontally. So we can horizontally slide either hot stream or cold stream. These you can do because we can treat the enthalpy axis as a relative scale because we are interested only in changes in enthalpy. Now if we do so what we are basically doing we are changing the minimum temperature difference between these two steps.

Note; in the first case the minimum vertical distance between the hot stream and the cold stream which was obtained as 20 degree Celsius. Now, I can change the relative positions by horizontally sliding these 2 curves. You can slide both the curves or let us say I am keeping the hot stream curve fixed and horizontally sliding the cold steam curve. So in this case in this relative position the vertical distance between the hot stream and the cold stream at this end is 10 degree Celsius.

So, the minimum, distance because in this as a go in this direction, the distance vertical distance between the streams increases. So the minimum distance between the streams in this case is 20 degree Celsius and in this case it is10 degree Celsius. Now these minimum temperature difference that is delta t minimum determines how much overlap will be there between the hot stream and the cold stream.

Which tells us; what will be the amount of heat that can be recovered. Also the amount of hot and cold utility requires will also be fixed. For this case delta T minimum is 20 degree Celsius. The heat recovered is 10 megawatt, hot utility target is 4 megawatt and the cold utility target is 2 megawatt. Note that in this, this is the region where the cold utility extends beyond the starting of the hot stream.

So, hot stream is not available for heating unit hot utility that is 4 megawatt. In this region the hot stream extends beyond the starting of the cold stream. So to cool down the hot stream, we need cold utility and the cold utility of 2 megawatt is required in this region. If I decrease the delta T minimum to 10 degrees Celsius, there will be greater degree of overlap. So heat recovered will be higher.

Now it is 11 compared to 10 before but you will now need less hot utility target and cold utility target as well because you have recovered more amount of heat.

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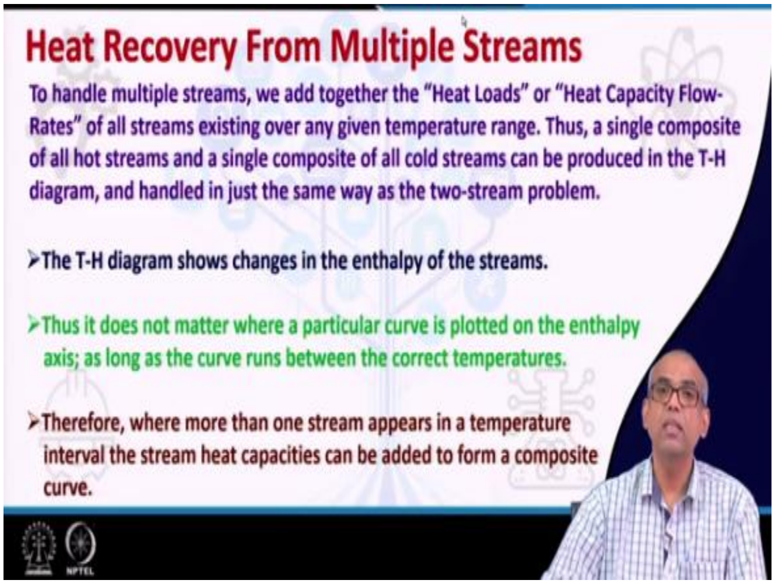

Now let us see how do I explain these concepts to heat recovery from multiple streams? To handle multiple streams, we simply add together the heat capacity flow rates of all streams existing over any given temperature range. So what we do is, we will plot all the individual streams. Let us say first let us talk about hot streams. So, all the individual hot streams will be plotted on the temperature versus enthalpy diagram.

Then over a given temperature range the streams heat capacity flow rates the CP values will be added and will be combining those individual hot streams into a combined single equivalent hot stream. So, single composite of all hot streams. And a single composite of all cold streams can be produced in the temperature enthalpy diagram. So that way you will combine all the hot streams into a single composite hot stream we can also combine all the cold streams into a single composite cold stream.

Then these two streams composite cold stream and the composite hot stream can be treated the same way we have treated the simple two stream problem. So let us see how we do that the temperature enthalpy diagram shows changes in the enthalpy of the streams. So therefore, it actually does not matter where a particular crowd is plotted on the enthalpy axis as long as the curve begins and ends at the correct temperatures. So as long as the curve; runs between the correct temperatures.

The starting temperature and the final ending temperature, it actually does not matter where a particular curve is plotted on the enthalpy axis. Therefore where more than one stream appears in a temperature interval the stream heat capacities that; means those CP values can be added to form a composite curve.

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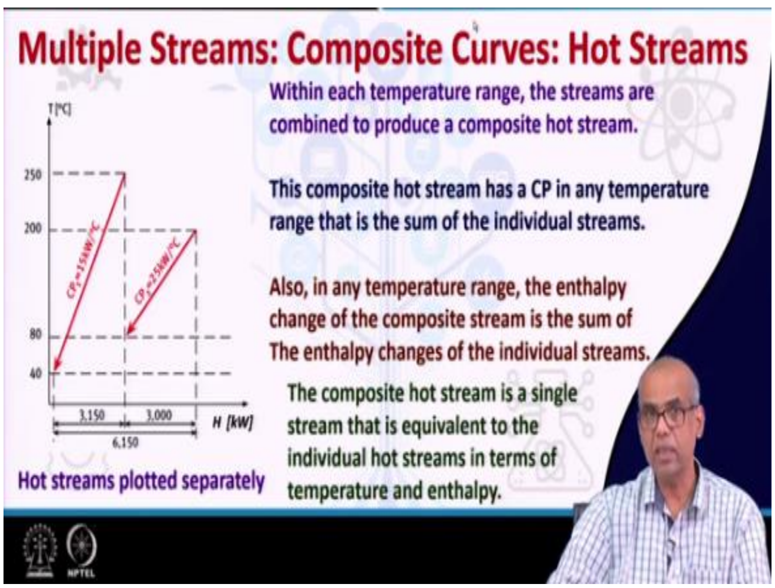

So let us look at this example, where we have plotted two hot streams on this temperature enthalpy diagram. So, two hot streams are plotted separately on this temperature and therapy diagram. Note, that depending on the starting or ending of the streams we have divided this temperature scale into various ranges. So we have now several temperature ranges. Here we have one temperature range and there is only one stream working only this stream.

Now next I have another temperature range. See this temperature range was introduced because we have this particular stream appeared in these temperature range. So here I have two streams working. Again, I have this temperature range, where we have only one stream available. Now within each temperature range, the streams will be combined to produce a composite hot stream.

Now the composite hot stream that we produce has a CP that means the heat capacity flow rates in any temperature range that is the sum of the individual streams. For example in this temperature range I have only one stream and if CP value is 15 kilowatt per degree Celsius. But in this temperature range I have two streams working with CP values of 15 and 25. So, in this region the composite stream will have the CP value 15 kilowatt per degree Celsius.

But in this region in this temperature range, the composite curve will have CP value equal to sum of 15 and 25, which is 40. So that is how will combine the individual streams; here hot streams in each temperature range by adding up the CP values available for the streams. Also in any temperature range then enthalpy change of the composite stream is the sum of the enthalpy changes of the individual streams.

So the composite hot stream becomes a single stream that is equivalent to the individual hot stream in terms of temperature and enthalpy. So, when I combine these two hot streams by adding up their CP values in each temperature range and also take care of the starting temperature and the ending temperature the composite hot stream that I get becomes a single equivalent composite stream, single equivalent hot composite stream.

And this composite hot stream is equivalent with the individual hot stream in terms of temperature value and enthalpy value. So now let us see how this composite hot stream will look like when I combine these two individual hot streams.

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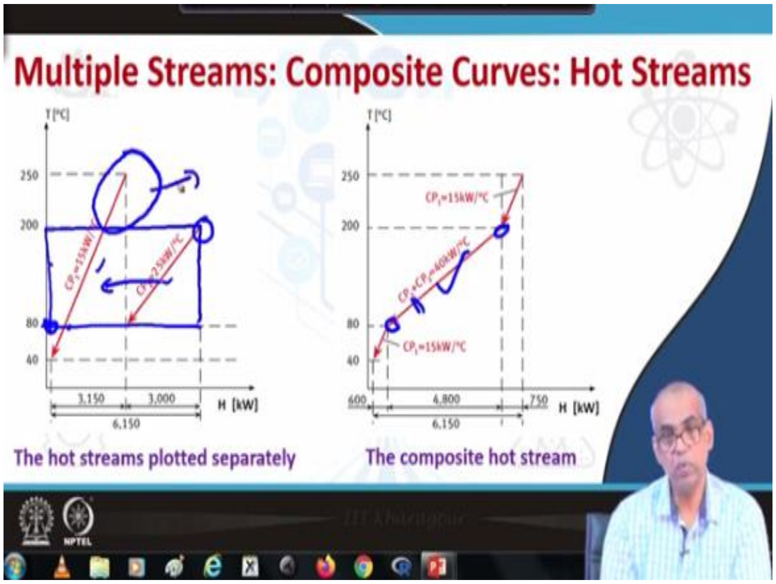

Now, let us consider how we construct a hot composite curve from these two individual hot streams. So the first hot stream has CP value of 15 kilowatt per degree Celsius and the other one has CP value of 25 kilowatt per degree Celsius. Note that in this temperature interval only 1 hot stream is working. So depending on the starting and ending of the streams. We have divided this temperature scale into temperature intervals.

In the next temperature interval we have service of both the hot streams and finally in the last temperature interval we have service of only 1 hot stream. So the composite curve that will get, the hot composite curve that I will get will have this starting and ending of temperature corresponding to this temperature interval. And also the enthalpy content will also be same. So, if I keep this in mind. And do the same thing for each and every interval I will be able to draw the composite curve.

Let us look at here first, in this interval I have, service of only 1 hot stream with CP value 15 kilowatt. So, this is that interval I basically have these curve unchanged in slope and starting ending temperature here. But the next one from 200 to 280 degrees Celsius I have service of 2 hot streams. So from this point I will draw a line for the hot composite curve with the slope of 1 by CP 1 plus CP 2.

Because hot composite curve will have CP values at 15 + 25 = 40. So In this region we can basically combine these two streams. So you can basically slide this thing and bring here and then can draw this line. And then finally from this point up to 250 degree Celsius I have only service of this hot stream so this slope remains unchanged here. So, this is how we can draw the hot composite curve.

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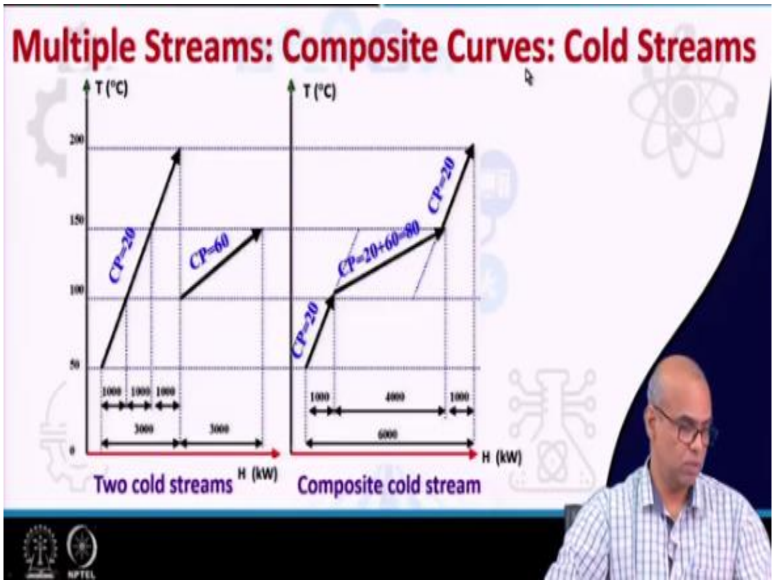

Exactly the same way we can find out the composite curve for cold streams. Again, we add up the CP values in each temperature range. So in this temperature range I have only one CP value which is 20, again in this temperature range I have one CP value, which is 20. But in these temperature ranges I have 2 CP values for 2 streams, which is 20 + 60 is 80. So, exactly the same way you can obtain the composite curve for cold streams and we will call that, cold composite curve.

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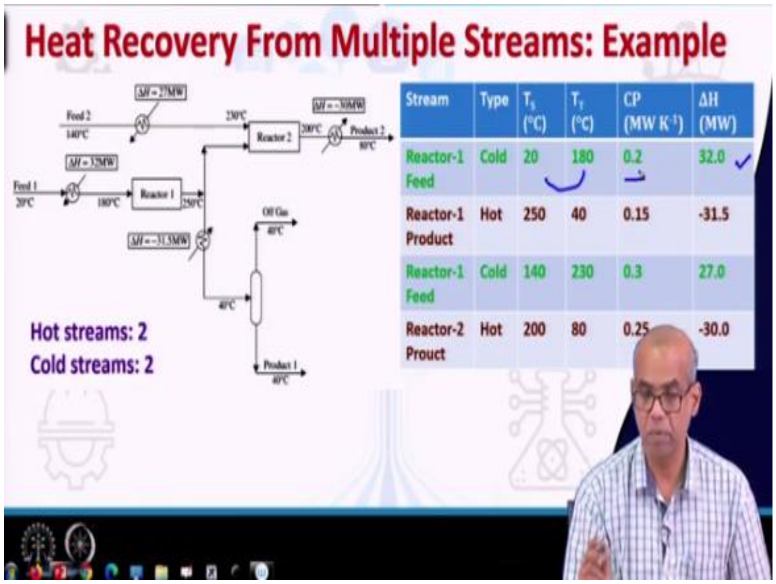

Now, let us take an example to understand these concepts where we will have the temperature and the enthalpy values taken from a simple process flow sheet. So consider this simple flow sheet for a process where you have two reactors and one separator. In this example the temperature and enthalpy values for the streams are shown. There are two hot streams, what are those hot streams?

Look at this stream, its temperature needs to be reduced from 250 degrees Celsius to 40 degree Celsius. So by definition hot streams are those which need to be cooled down. So, this is one hot stream and we have another hot stream from the reactor 2 which needs to be cooled down from 200 degrees Celsius to 80 degrees Celsius. So, these are the two hot streams and then there are two cold streams; that means the streams whose temperature needs to be heated up the temperature streams which needs to be heated up.

So one is feed stream to reactor one which needs to be heated from 20 degrees to 180 degree Celsius and another is feed to reactor 2 which is heated from 140 degrees Celsius to 230 degrees Celsius. So there are these two hot streams and these two cold streams all the temperatures are shown as well as the enthalpy change values are also shown. So you can extract this data and form a table.

So reactor 1 feed and reactor 2 feed are cold streams and the reactor 1 product and the reactor 2 product streams are hot streams. So their temperatures are also shown. We just extract the data from the flow sheet and prepare this table. The CP values which are product of mass flow rate times specific heat capacity are also shown and we assume this CP values to be constant. Note that CP values are constant;

So these streams will represent straight lines or temperature enthalpy diagram. If the CP value is changes appreciably we will have a non-linear and enthalpy temperature relationship which can be approximated by piecewise linear segments. So note that this delta H values are nothing but the difference between the two temperatures target temperature and the source temperature multiplied by the CP value. So these data tableted. Now we are able to plot this.

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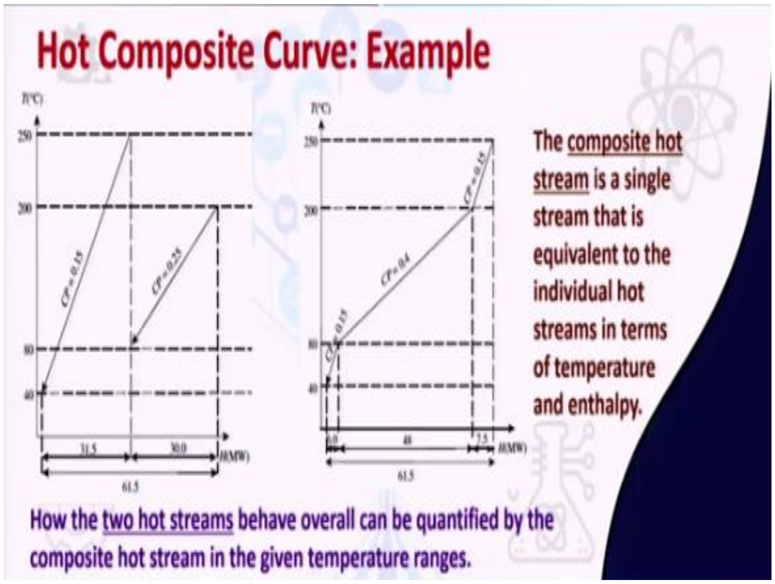

So we have now first plotted the hot streams. So what was the temperature of the two hot streams? One is 250 to 40 another was 200 to 80. So, we plot first hot stream 250 to 40 and 200 to 800, their CP values are also shown. So you can have more number of streams here. But the way we form the hot composite curve will be exactly same. Now how the two hot streams behave overall can be quantified by the composite hot stream in the given temperature range.

So let us get the hot composite stream. Note that we have found out exactly the same way we have a single hot stream working in this temperature range. And then this represents the stream, which is which has combined CP values and finally here again I have the single hot stream with

CP value 0.15. So you will notice that these two slopes will not be different. Note that we cannot change the slope of these streams on the temperature enthalpy diagram.

Similarly here, the slopes will only change when there is some changes in this range with this temperature range. For example here you have start or finishing of one additional stream. So, that is why you have a stream with different slope compared to these and these essentially have combined these two streams. So the composite hot stream that we obtain now is a single stream which is equivalent to the individual hot streams in terms of temperature and enthalpy.

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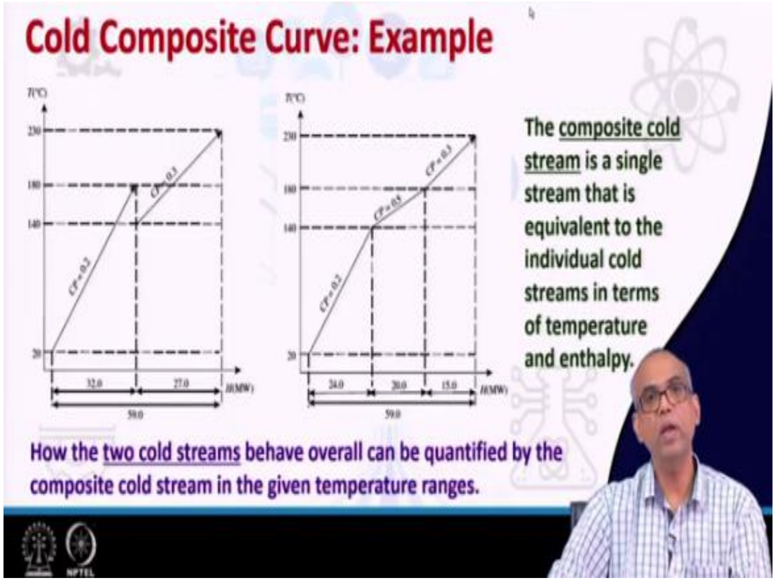

Exactly same way let us now find out the cold composite curve and the cold composite curve will be equivalent to the individual cold composite, cold streams in terms of temperature and enthalpy.

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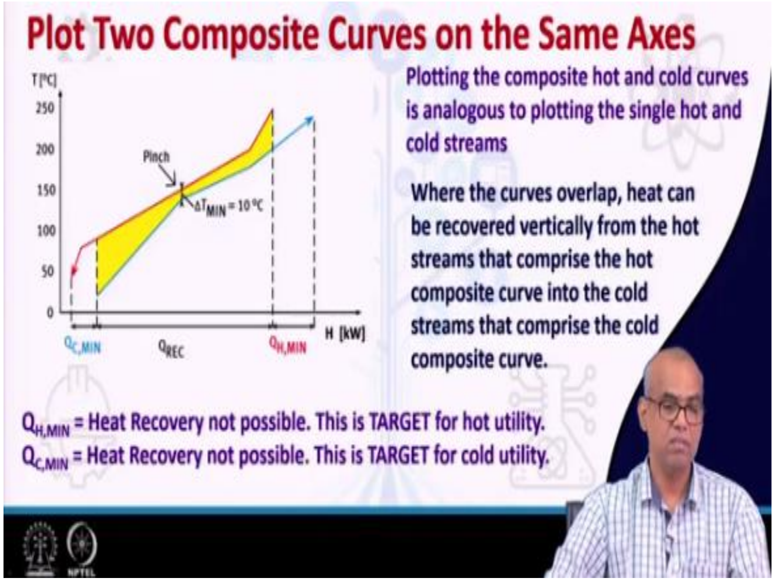

Now let us plot this two composite curves on the same axis, like in case of two stream problems, we plot it, the hot stream and the cold stream I had only one hot stream, I had only one cold stream so I plot in the hot stream and cold stream on the temperature enthalpy diagram and can infer the heat recovery and the heat duties for the, utilities or the loads for the utilities. So, I follow the same approach.

I have now combined all the hot streams to single composite stream and I have combined all the cold streams to a single cold composite stream. So let us now plot these two composite streams on the same axis. And again we have to plot for a given delta T minimum value. So plotting the composite hot and the composite cold curves is similar to plotting the single hot and single cold streams that we have done earlier.

So now again, we will analyze the situation for this multiple streams the same way we have done for the two steam problems. Now where these two composite curves overlap. That means the shaded region in the figure, it shows that heat can be recovered vertically from the hot stream into the cold streams. So this region where these two composite curves overlap heat can be recovered vertically from the hot streams comprising the hot composite curve into the cold streams that constitute the cold composite curve.

We can also infer the target for hot utility from the region where the cold composite curve is extended beyond the beginning of the hot composite curve. So this gives me the target for hot utility because in this region heat recovery is not possible. Similarly this region; where the hot composite curve extends beyond the beginning of the cold composite curve. Heat recovery again is not possible.

And hot stream here must be cooled down by the cold utility. So this represents the target for cold utility. So you can exactly same way can infer or analyze the amount of heat that can be recovered and the target for hot utility as well as target for cold utility.

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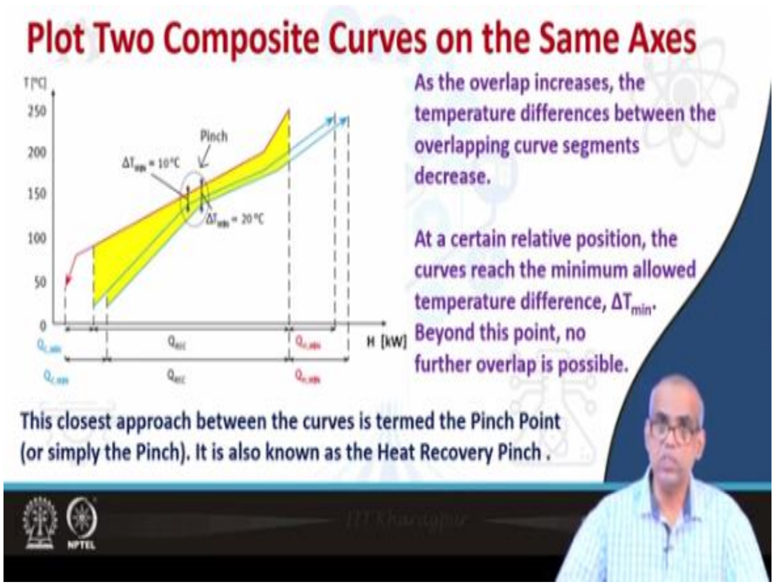

The larger the; value of the delta T minimum the smaller the possible maximum heat recovery. Note that the delta T minimum as you see in this figure will be larger by sliding the cold stream to the right hand side. So this will decrease the region of overlapping between these two composite streams. So, that is why the larger the value of the delta T minimum the smaller the possible maximum heat recovery.

If we specify the minimum utility heating the minimum cooling utility or the minimum temperature difference, it will fix the relative position of the two composite curves and hence the maximum possible amount of heat recovery. The defined heat recovery targets are related to the specified value of the delta T minimum. If the value of the delta T minimum is increased then the minimum utility requirements also increases and the potential for maximum recovery drops.

So the maximum amount of heat recovered is possible when the delta T minimum is set to its minimum value. As you slide horizontally; either the hot composite curve or the cold composite curve the overlap between these two curves changes. As the overlap increases; the temperature difference between these two curves decreases. So with decreasing value of the delta T minimum**(FL: 33:09)**

As you slide; either the hot composite curve or the cold composite curve horizontally the overlap between these two curves changes. As the overlap; increases the temperature difference between these two overlapping curves decreases. So as the overlap **(FL: 34:15)** as we slide horizontally either the hot composite curve or the cold composite curve. The overlap between these two curves changes.

As the overlap increases the temperature difference between the overlapping curves segments decrease. As the overlap decreases; the temperature difference between these two curves increases. Now at a certain relative position the curves reach the minimum allowed temperature that means at a gate at a certain relative positions the vertical distance between these two curves or the minimum vertical distance between these two curve will be equal to the minimum allowed temperature difference, that is specified delta T minimum.

Beyond this point further overlap is not possible you cannot decrease the minimum temperature difference. Vertical temperature difference between these two curves beyond that value. So further overlap is no more possible this closest approach between the hot composite curve and the cold composite curve is called pinch point.

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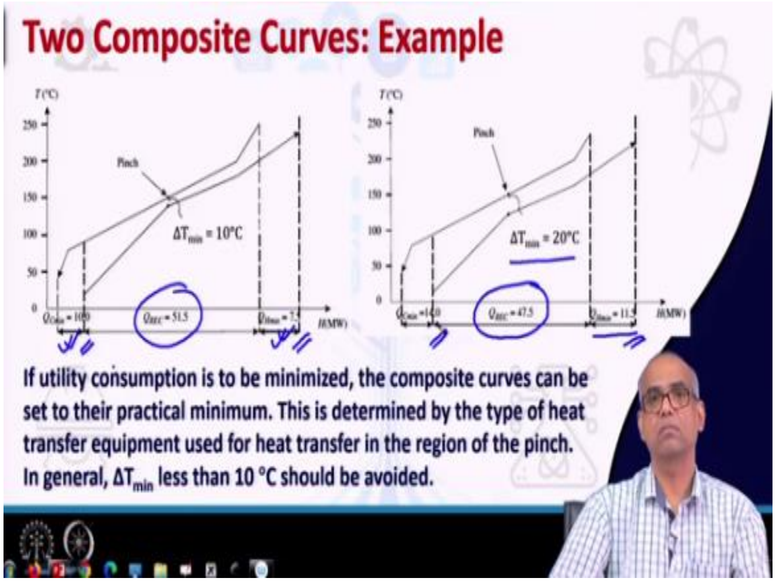

Now, let us take back that example and find out these composite curves for two different delta T minimum; one is 10 degrees celsius and this source for 20 degree Celsius. Look at the pinch points, for the first case where the delta T minimum is set to 10 degrees Celsius. So delta T the 10 degree Celsius is obtained here. So this is 10 degree Celsius, the pinch point. In this case the amount of heat recovery is 51.5 megawatt.

The hot utility duty is 7.5 megawatt and the cold utility target is 10 megawatt. Now if I increase the value of the delta T minimum from 10 degree Celsius to 20 degree Celsius, I will have less amount of overlap between this 2. So when I have less amount of overlap between these 2. It means that the heat recovery will decrease. So now I have the reduce heat recovery of 47.5 megawatt.

So, obviously the target for the, hot utility as well as target for the cold utility will increase. So the target for cold utility increases from 7.5 megawatt to 11.5 megawatt and target for cold utility increases from 10 megawatt to 14 megawatt. If we want to minimize the consumption of utilities hot utility or cold utility the composite curves can be set to the minimum delta T possible value. So, delta t minimum must be set appropriately.

So that we can minimize the consumption of hot and cold utility but note that we must set the delta T minimum to their practical minimum what we mean by the practical minimum is as follows. The delta T minimum or the practical delta t minimum is often determined by the type of heat transfer equipment used for the heat transfer in the region of the pinch. So depending on the type of heat transfer equipment we are using there will be a practical minimum values for the delta t minimum.

For example, when I use a salient tube heat exchanger a value less than 10 degree Celsius should be avoided.

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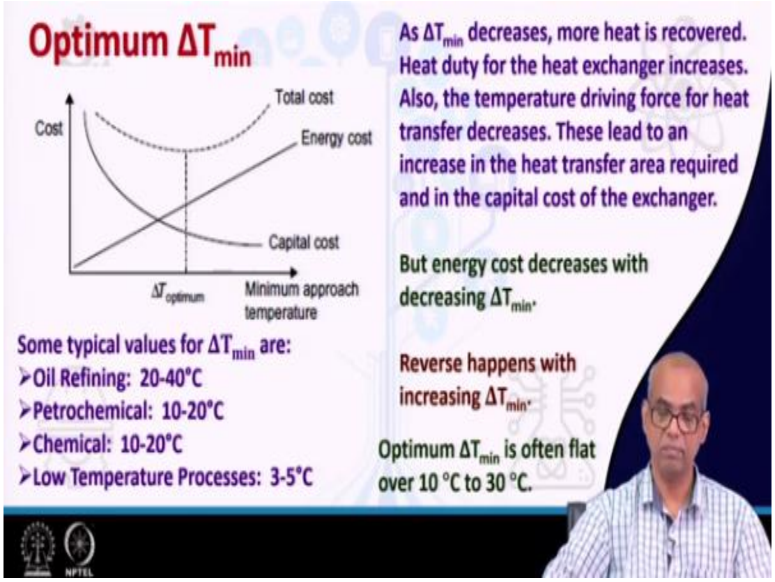

When you decrease the delta T minimum values we see that there is greater degree of overlap between the two composite curves. So, thus more and more amount of heat will be recovered. So when more amount of heat needs to be recovered will be recovered heat duty for the heat exchanger will increase. But you also see that the driving force for heat transfer decreases delta T minimum decreases, driving force for heat transfer decreases.

Now these things will lead to increase in the heat transfer area required. So thereby the capital cost of the heat exchanger will increase. So capital cost of the heat exchanger will increase as I decrease the delta T minimum value. But when I decrease the delta T minimum, value I recover more and more amount of heat. So the; load on the cooling and hot utility decreases. So the energy cost decreases with decreasing value of the delta T minimum.

So with decreasing value of delta T minimum energy cost decreases, but the capital cost of the exchanger increases. Exactly the reverse happens when the delta t minimum value is increased. So when I add these two cost to obtain the total cost and plot the total cost versus delta T minimum when I add these two individual cost capital cost of exchanger and the energy cost with increasing value of the delta t minimum.

I obtain the total cost, so the total cost now is plotted as a function of delta T minimum by adding up to individual cost as a functions of delta T minimum. So, I see that there is a minimum on this total cost curve. This gives me the corresponding delta T minimum gives me the delta T optimum. Typically this optimum happens over a flat region and that flat region for a range of chemical process happens between 10 degrees Celsius to 30 degree Celsius.

So here are some typical values for the delta T minimum for various chemical process industries Oil Refining delta T minimum is typically taken as 20 to 40 degree Celsius, petrochemical 10 to 20 degrees Celsius, chemical process industry is 10 to 20 degree Celsius low temperature processes 3 to 5 degrees Celsius. So note that this will require special type of heat transfer equipment.

So these values are representative values the typical representative values for the delta T minimum in various process industries. So with this we stop our discussion here.