Plant Design and Economics
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Lecture No -48
The Problem Table Method

Welcome to lecture 48 of plant design and economics as of now we have learned about construction of composite curve. The composite curve can be used to determine the minimum hot utility, minimum cold utility required as well as the maximum energy that can be recovered between hot streams and cold streams. Now the composite curve method is a graphical method. In today's lecture we will learn about an algebraic method which is called the problem table method.

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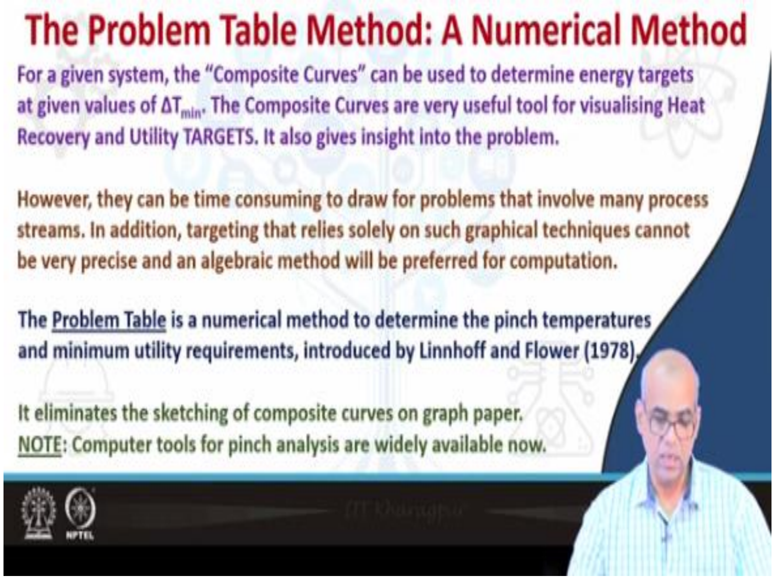

The Problem Table Method: A Numerical Method

For a given system, the "Composite Curves" can be used to determine energy targets at given values of ΔT_{min}. The Composite Curves are very useful tool for visualising Heat Recovery and Utility TARGETS. It also gives insight into the problem.

However, they can be time consuming to draw for problems that involve many process streams. In addition, targeting that relies solely on such graphical techniques cannot be very precise and an algebraic method will be preferred for computation.

The Problem Table is a numerical method to determine the pinch temperatures and minimum utility requirements, introduced by Linnhoff and Flower (1978).

It eliminates the sketching of composite curves on graph paper.
NOTE: Computer tools for pinch analysis are widely available now.

For a given system the composite curves can be used to determine energy targets at given values of minimum delta T, delta minimum. We have seen that the composite curves are very useful tool for visualizing the heat recovery and the minimum hot utility target as well as minimum cold utility target. This also gives an inside into the problem however since this is a graphical method. When you have many streams, several hot stream and several cold streams the construction of composite curve using a graphical method will be time consuming.

Although these days there are several softwares which can be put to use and you actually do not have to take a graph paper and draw the composite curves by hand. Also when you are using a method; that is solely graphical, solely based on graphical techniques. It cannot be very precise compared to an algebraic method, so algebraic method is generally preferred for the purpose of computation.

Here also for the purpose of computation of utility targets; the pinch temperature, the algorithmic is method has been introduced and will talk about one method known as the problem table method, which is a numerical method to determine the pinch temperature and the minimum utility requirements, which was introduced by Linnhoff and Flower. The use of problem table method will completely eliminate the necessary for using graph papers or sketching or composite curves on a graph paper.

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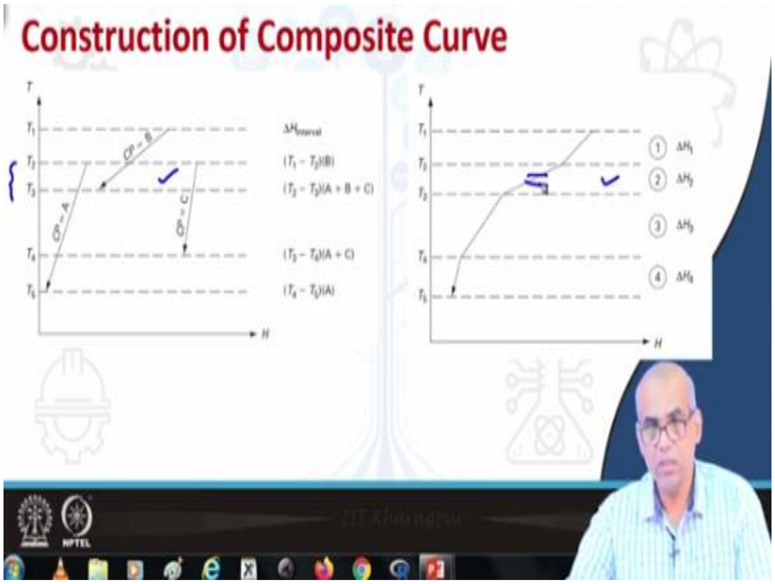

Construction of Composite Curve

So, we have already seen the construction of composite curves. We have seen how this composite curve in this particular example, the hot composite curve was constructed on the basis of the informations on temperatures and CP values, heat capacity values which gives us the enthalpy informations. So, for example in this interval between T1 to T2. You have only a single hot stream in operation.

So, in the composite curve or in the hot composite curve the contribution comes only from this stream. So the H value in this interval in composite curve as well as in this original TH diagram where multiple streams are there are same and that is T 1 minus T 2 multiplied by the CP value of B. But when you come to the next interval here you see that 3 streams are in service. So, the H, value will be T 2 minus T 3 multiplied by CP of A plus CP of B plus CP of C.

You know that the slope of these lines on TH diagram depends on the CP values slope equal to reciprocal of CP. So, here you have align with different slope on the composite TH diagram.

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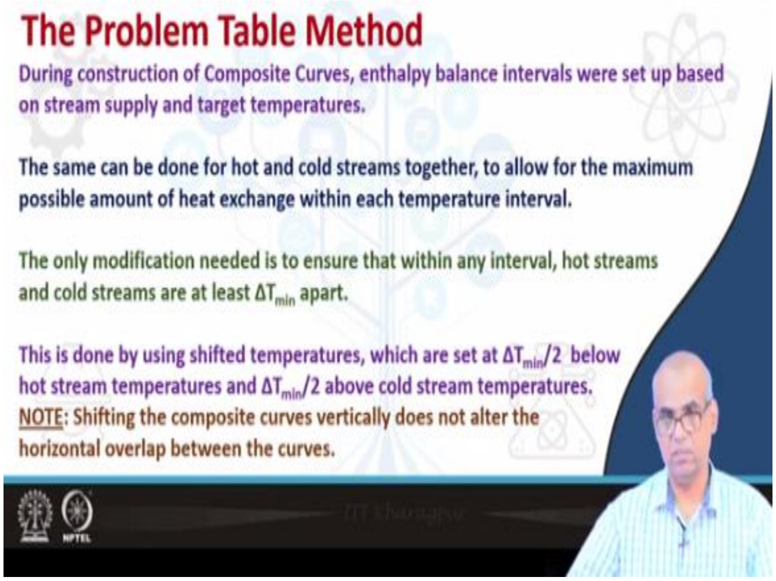

The Problem Table Method

During construction of Composite Curves, enthalpy balance intervals were set up based on stream supply and target temperatures.

The same can be done for hot and cold streams together, to allow for the maximum possible amount of heat exchange within each temperature interval.

The only modification needed is to ensure that within any interval, hot streams and cold streams are at least ΔT_{min} apart.

This is done by using shifted temperatures, which are set at $\Delta T_{min}/2$ below hot stream temperatures and $\Delta T_{min}/2$ above cold stream temperatures.
NOTE: Shifting the composite curves vertically does not alter the horizontal overlap between the curves.

So this way on the basis of the temperature and the enthalpy informations we could construct the composite curves. So again, if you look at this you will see that, these diagrams where we have plotted individual streams and this diagram where I have plotted a composite curve both the comes equivalent in terms of temperature and enthalpy. So if you look at this part and the corresponding part in the composite curve.

Both have the same enthalpy value and both started and ended between the same initial and final temperature meaning T 1 and T 2. So this H values are same in all these intervals that are shown on the diagram. So, to summarize during the construction of composite curves enthalpy balance intervals were set up based on streams supply temperature and streams target temperature. We can do the same thing for both hot and cold streams taken together to allow for the maximum possible amount of heat exchange within each interval.

So in the previous case when during the construction of composite curve we did separately for hot streams separately for cold streams. Now, we are saying the same concept can be extended to both hot and cold streams taken together to allow for the maximum possible amount of heat exchange with each within each temperature interval. However, one modification must be ensured that within any interval hot streams and cold streams temperature must be at least different by the minimum temperature that has been set; that means delta T minimum.

So whatever delta T minimum has been set by you, we must ensure that within any interval hot streams and cold streams temperature must be apart by this delta T minimum that has been set. Now how to ensure that? Now this can be ensured if I shift the, original temperatures as follows. What we do is we decrease the hot streams temperature by delta T minimum by 2. And increase the cold streams temperature by delta T minimum by 2.

So thereby you may ensure that in any interval always the shifted temperature of the hot stream and the shifted temperature of the cold stream will at least be different by delta T minimum. Note that the shifting, the composite curves vertically does not alter the horizontal overlap between the curves. So when I shift the original temperatures by delta T minimum by 2 either increase it or decrease it.

I increase it for cold stream temperature; I decrease it for hot stream temperatures. What I am basically doing is I am shifting the composite curves vertically. When I shift the composite curves, vertically note that the horizontal overlapping between the curves do not change. So the minimum hot utility target, minimum cold utility target, they do not change.

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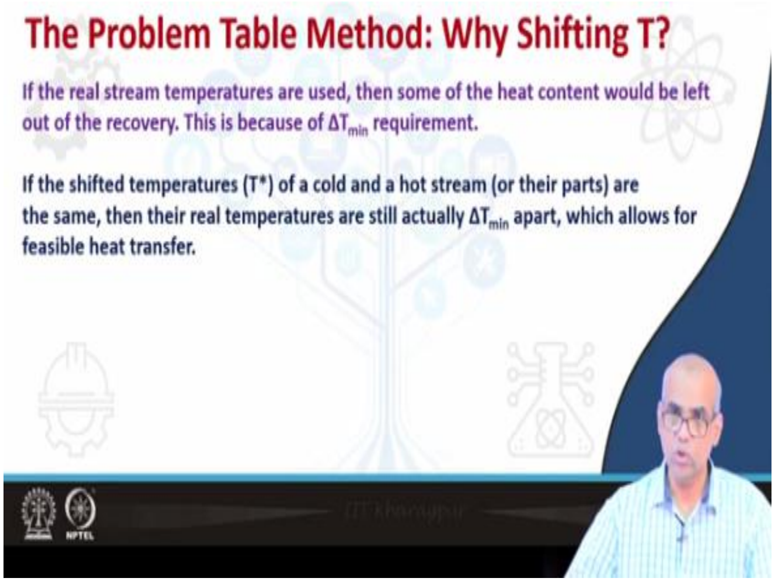

The Problem Table Method: Why Shifting T?

If the real stream temperatures are used, then some of the heat content would be left out of the recovery. This is because of ΔT_{min} requirement.

If the shifted temperatures (T^*) of a cold and a hot stream (or their parts) are the same, then their real temperatures are still actually ΔT_{min} apart, which allows for feasible heat transfer.

But why do we do this? Because to ensure that the; two temperatures are at least upper by delta T minimum, two shifted temperatures. So if the real temperatures are used then some of the heat content would be left out of recovery. This is because delta T minimum requirement. If the shifted temperatures of cold and hot streams or their parts are the same then the real temperatures we know that they are still different by delta T minimum.

Because I have changed them accordingly so even if the shifted temperature of cold stream and hot steam are same we know that they are actually different by delta T minimum that has been set. So that will allow feasible heat transfer.

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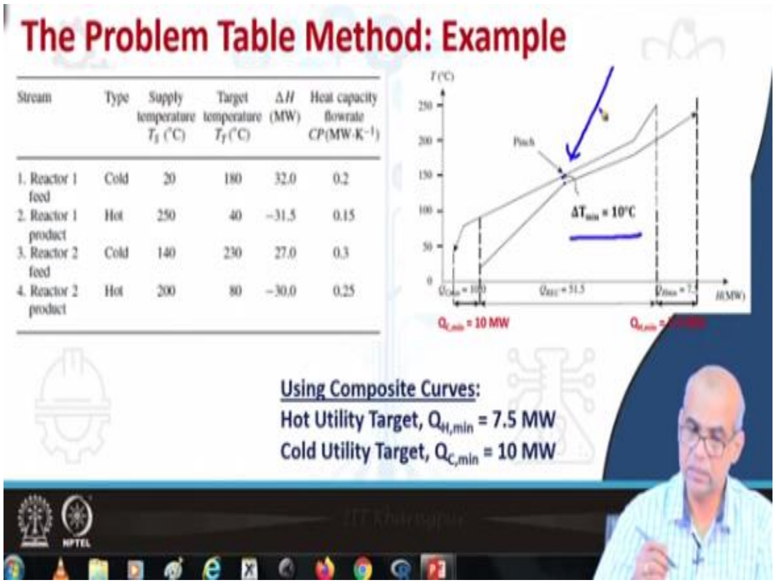

The Problem Table Method: Example

Stream	Type	Supply temperature T_S (°C)	Target temperature T_T (°C)	ΔH (MW)	Heat capacity flowrate CP (MW·K^{-1})
1. Reactor 1 feed	Cold	20	180	32.0	0.2
2. Reactor 1 product	Hot	250	40	−31.5	0.15
3. Reactor 2 feed	Cold	140	230	27.0	0.3
4. Reactor 2 product	Hot	200	80	−30.0	0.25

Using Composite Curves:

Hot Utility Target, $Q_{H,min}$ = 7.5 MW

Cold Utility Target, $Q_{C,min}$ = 10 MW

So now we will take an example to demonstrate the use of the problem table method which is a numerical method and we will go through the algorithm by taking an example. So we take this example, which I have already seen before in our previous lectures. So I have two streams basically this is the problem where you have two reactors and one separator. So you have to feed streams to reactors and to product streams from the reactor.

So there are two cold streams two hot streams. So reactor 1 feed is cold stream, reactor 2 feed is cold stream. And reactor 1 product stream is hot and reactor 2 product is another hot stream, so two hot streams two cold streams. So their supply temperatures target temperatures are all given heat capacity flow rates are also given. Now using composite curve; for a target or set delta T minimum equal to 10 degrees Celsius. We see that the, hot utility target is 7.5 megawatt and the cold utility target is 10 megawatt.

Energy recovery between these two streams is 51.5 megawatt. So this was already solved using composite curve method, so we will solve this again using the problem table method and we must get back the same results. Also note the pinch temperature, this point so when I say that the delta T minimum is the degree Celsius that means at this point the vertical distance between the composite curve and the hot composite curve and the cold composite curve is exactly 10 degrees Celsius.

So at this relative position between the cold composite curve and the hot composite curve. The vertical distance between these two composite curves is 10 degrees Celsius. So we call this pinch, so there is pinch temperature for the hot stream pinch temperature for the cold stream. So they are different by 10 degrees Celsius.

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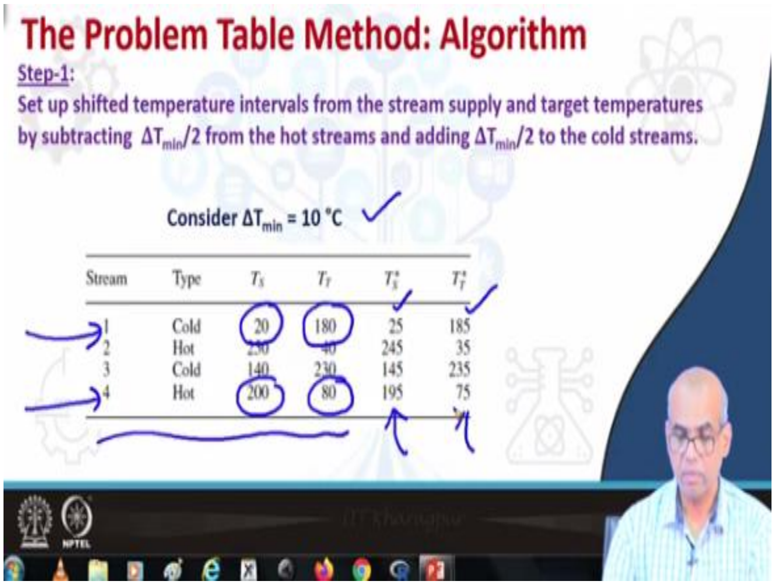

The Problem Table Method: Algorithm

Step-1:

Set up shifted temperature intervals from the stream supply and target temperatures by subtracting $\Delta T_{min}/2$ from the hot streams and adding $\Delta T_{min}/2$ to the cold streams.

Consider ΔT_{min} = 10 °C ✓

Stream	Type	T_S	T_T	T_S^*	T_T^*
1	Cold	20	180	25	185
2	Hot	250	40	245	35
3	Cold	140	230	145	235
4	Hot	200	80	195	75

So let us now go through the algorithm, as we discuss that instead of working on absolute temperatures will be working with shifted temperature, so in the step one of the algorithm we set up shifted temperature intervals from the streams supply temperature and the streams target temperatures by subtracting delta T minimum by 2 from the hot streams and adding delta t minimum by 2 to the cold streams.

So this was the, given stream supplied temperature and target temperature, for example consider stream number one which is a cold stream which is available at 20 degrees Celsius and must be heated up to 180 degrees Celsius. So the shifted temperature; the shifted supply temperature and the shifted target temperature will be obtained by adding delta T minimum by 2 it is a cold stream.

So the shifted temperature will be obtained by adding delta T minimum by 2 delta T minimum is 10 degrees Celsius that we have set so we must add 5 degree Celsius to both this supply temperature and target temperature, so I obtain 25 degree Celsius and 185 degree Celsius. Similarly let us consider the stream number 4, which is a hot stream. So it must be cooled down from 200 degree Celsius to 80 degrees Celsius.

So it is a hot stream so I must subtract delta T minimum by 2 from both supply and target temperature, so I obtained 200 minus 5, 195 degree Celsius and 80 minus 5, 75 degree Celsius.

So this is how I obtain the shifted temperature intervals.

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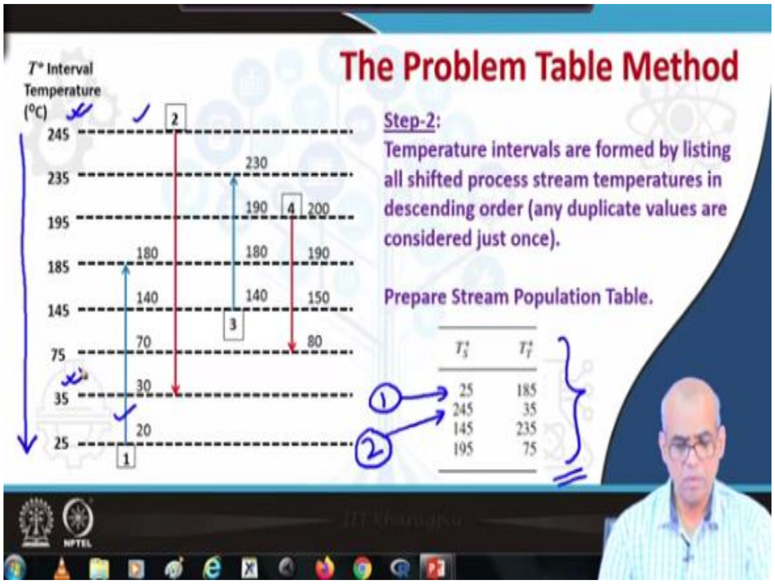

The Problem Table Method

Step-2:
Temperature intervals are formed by listing all shifted process stream temperatures in descending order (any duplicate values are considered just once).

Prepare Stream Population Table.

	T_S^*	T_T^*
①	25	185
②	245	35
	145	235
	195	75

So now temperature intervals are formed by listing all the shifted process stream temperatures in descending order. Also any duplicate values will be considered just once. So these are the shifted temperatures that we obtained in previous table. So we prepare the temperature intervals by listing all these shifted process stream temperatures in the descending order as shown here. And then you prepare the stream population table.

So, look at the hot stream temperatures; 1, 2 3 4. So this is stream number 1. So this goes from 25 degree Celsius to 180 degree Celsius, this is the cold stream so which is get from actual temperature 20 degree Celsius to 180 degree Celsius. So shifted temperature is 25 degree to 185. Similarly let us consider stream number 2, which is a hot stream which is cooled from 250 degree Celsius to 40 degrees Celsius in terms of shift temperature from 245 to 235.

Because you have reduced 5 degree Celsius because it is hot stream. Similarly another cold stream and another hot stream are shown. So we prepare the stream population table.

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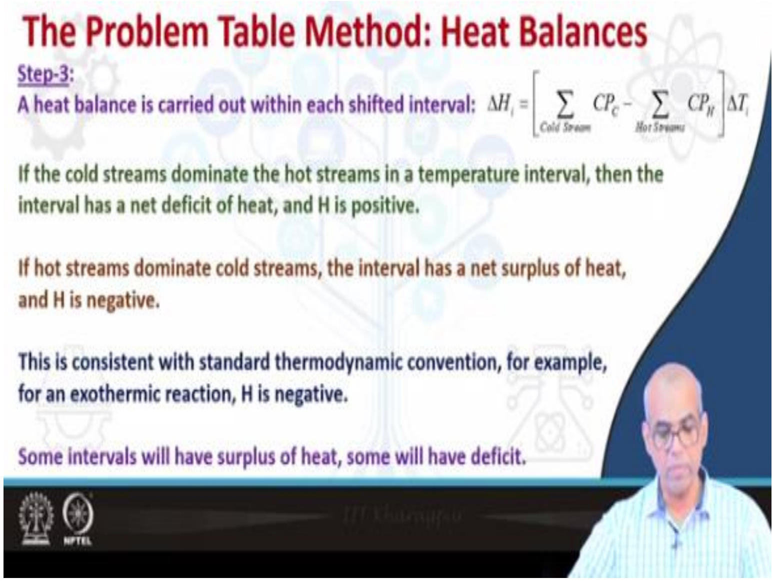

The Problem Table Method: Heat Balances

Step-3:

A heat balance is carried out within each shifted interval: $\Delta H_i = \left[\sum_{\text{Cold Stream}} CP_C - \sum_{\text{Hot Streams}} CP_H \right] \Delta T_i$

If the cold streams dominate the hot streams in a temperature interval, then the interval has a net deficit of heat, and H is positive.

If hot streams dominate cold streams, the interval has a net surplus of heat, and H is negative.

This is consistent with standard thermodynamic convention, for example, for an exothermic reaction, H is negative.

Some intervals will have surplus of heat, some will have deficit.

Now we will performing heat balance within each shifted interval and the heat balance can be performed by this equation which says that you sum up all the heat capacities flow rates for cold stream then subtract the sum of all it capacity flow rates for the hot streams and then multiply the difference by the difference of temperature in the interval. So, this will give you delta H 1, delta. H 2, delta H 3, etcetera for each interval.

So, you will look at the interval table and see in each interval how many cold streams are there and how many hot streams are there? You will add up there. CP values and then you can find out this difference and then just multiply by the delta T i values for that interval. So thereby you can perform the heat balance for the interval. If the cold streams dominate the hot streams in a particular temperature interval.

Then the interval will be positive because if this dominates then the interval delta H value will be positive and we will call that this interval has a net deficit of it. Similarly if hot stream dominates over cold streams in a particular interval then that particular intervals delta H value will be negative and will say that interval has the net surplus of it. Now this notation or convention is consistent with standard thermodynamic convention, for example for an exothermic reaction H is negative.

Now, once you perform the heat balance according to this scheme, you will see the sum intervals will have surplus of it and some intervals will have deficit of it.

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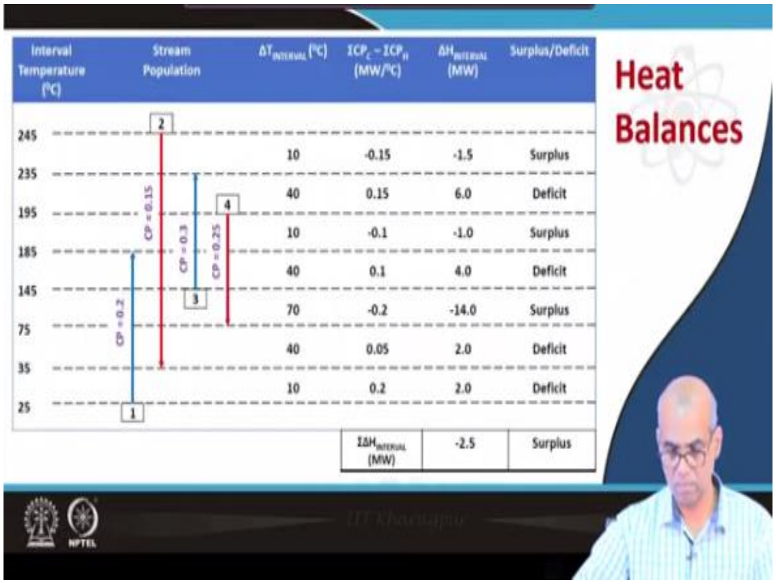

Heat Balances

Interval Temperature (°C)	Stream Population	$\Delta T_{INTERVAL}$ (°C)	$\Sigma CP_C - \Sigma CP_H$ (MW/°C)	$\Delta H_{INTERVAL}$ (MW)	Surplus/Deficit
245					
		10	-0.15	-1.5	Surplus
235					
		40	0.15	6.0	Deficit
195					
		10	-0.1	-1.0	Surplus
185					
		40	0.1	4.0	Deficit
145					
		70	-0.2	-14.0	Surplus
75					
		40	0.05	2.0	Deficit
35					
		10	0.2	2.0	Deficit
25					

$\Sigma\Delta H_{INTERVAL}$ (MW)	-2.5	Surplus

Now, let us understand that heat balance here. So the entire table is shown now, including the stream population. So, these are the interval temperatures those shifted temperatures. So, this is the temperature interval 245 minus 235 is 10, 235 minus 195 is 40 so on and so forth. Now, let us find out this difference. This difference is what? Sum of CP values for cold stream minus sum of CP values for hot stream.

Look at the first interval between 245 to 235 if the temperature interval. We have only one hot stream in service with CP value 0.15. So this gives us 0 minus 0.15 that is why we have minus 0.15. So delta H will be this point minus 0.15 multiplied by delta t which is minus 1.5 according to our convention we have surplus heat there. Similarly let us consider next interval where delta T is 40 we have one hot stream one cold stream in service.

So, what will be this value this will be 0.3 Minus 0.15 cold stream CP minus cold stream CP, so it becomes 0.15 and multiplied by 40 you get delta H for the interval as 6. This is positive so following our convention this sets heat deficit. Similarly when you have several streams such as; in these intervals you have two cold streams and two hot streams, so you must find out this difference appropriately.

So thereby following this you prepare this entire table and finally this delta H we see that we get as minus 2.5 that means it has surplus heat. So these values must agree with the overall heat balance for the data that we were given here. So find out this some of these 4 quantities so this becomes if we do this it becomes 0.5. If we take the difference between these two it becomes minus 3, but I have 0.5 so minus 2.5. So this agrees well with the overall heat balance.

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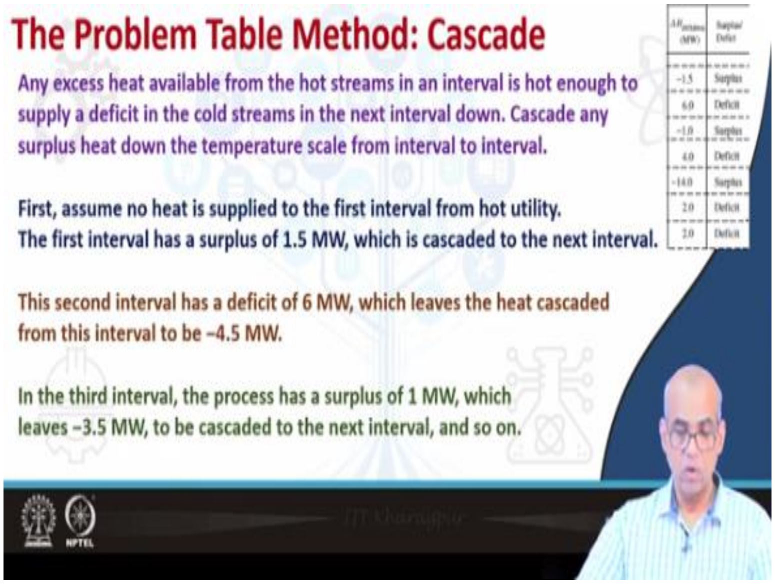

The Problem Table Method: Cascade

Any excess heat available from the hot streams in an interval is hot enough to supply a deficit in the cold streams in the next interval down. Cascade any surplus heat down the temperature scale from interval to interval.

First, assume no heat is supplied to the first interval from hot utility.
The first interval has a surplus of 1.5 MW, which is cascaded to the next interval.

This second interval has a deficit of 6 MW, which leaves the heat cascaded from this interval to be –4.5 MW.

In the third interval, the process has a surplus of 1 MW, which leaves –3.5 MW, to be cascaded to the next interval, and so on.

$\Delta H_{interval}$ (MW)	Surplus/ Deficit
–1.5	Surplus
6.0	Deficit
–1.0	Surplus
4.0	Deficit
–14.0	Surplus
2.0	Deficit
2.0	Deficit

Now the heat balance in each interval ensures the maximum energy recovery within that interval but heat can also be transferred between the intervals. So any excess heat available from the hot streams in an interval is hot enough to supply a deficit in the cold streams in the next interval down the line. So what we can do is we can cascade any surplus heat down the temperature scale from one interval to another.

For example the part of that table is shown here. Let us first assume that no heat is supplied to the first interval from hot utility. The first interval as a surplus of 1.5 megawatt. So what will do is will cascade this to the next interval. But the next interval has a deficit of 6 megawatt. The first one will cascade 1.5 but the next one has deficit of 6, the deficit of 6 megawatt. Now when this is also cascaded the heat that leaves after this cascade will have value minus 4.5.

Because we had 1.5 excess in the first interval and we have deficit 6 in the second interval. In the third interval which has minus 1 as excess or surplus. So if we cascade then the heat that will leave the third interval will have minus 3.5 megawatt. So this again can be cascaded to the next interval and this will go out.

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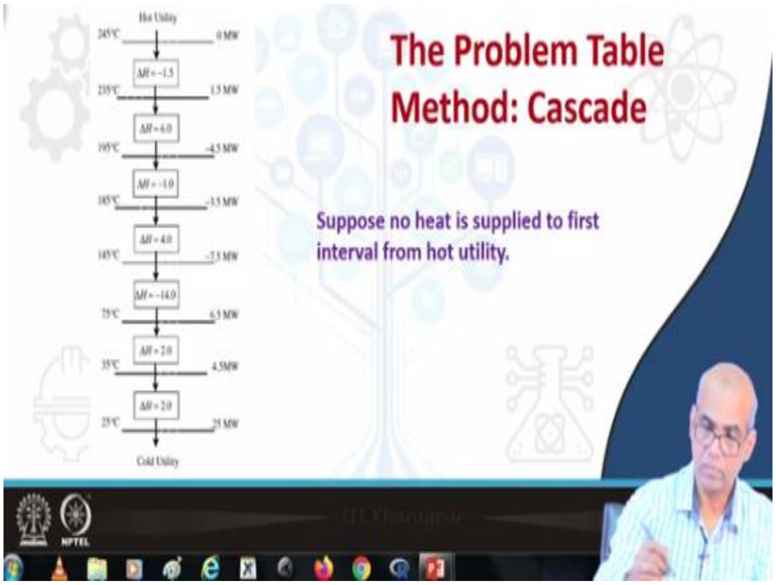

The Problem Table Method: Cascade

Suppose no heat is supplied to first interval from hot utility.

So, this is clearly seen from here. So we suppose that no heat is supplied to the first interval from the hot utility. So this interval has excess or surplus heat of 1.5 megawatt, which is cascaded to the next interval. So the next interval as deficit of 6. So in this is cascaded, the heat that leaves the second interval is minus 4.5. This is cascaded to the third interval which has surplus of minus 1.

So this heat when leaves this third interval after being cascaded. We will have value minus 3.5. Now this is cascaded to the next interval which has deficit of 4. So these when cascaded will have heat value as minus. 7.5. Now, this is considered to the next interval, which is excess of minus 14. So heat leaving that cascade will now have value plus 6.5 megawatt. The next one will have deficit 2.

So when cascaded the 6.5 megawatt in the previous interval will go down to 4.5 megawatt. So this way, it will be done down the temperature scale. But now we will see that some heat values are positive some evaluation negative.

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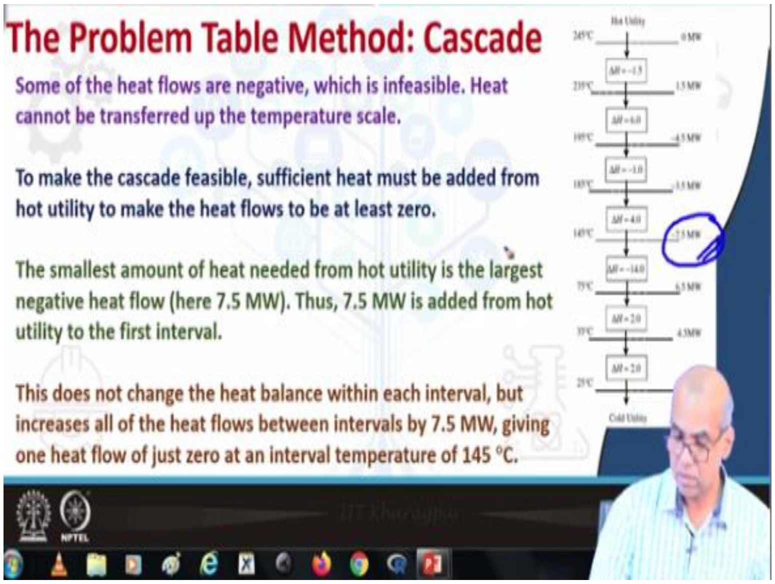

The Problem Table Method: Cascade

Some of the heat flows are negative, which is infeasible. Heat cannot be transferred up the temperature scale.

To make the cascade feasible, sufficient heat must be added from hot utility to make the heat flows to be at least zero.

The smallest amount of heat needed from hot utility is the largest negative heat flow (here 7.5 MW). Thus, 7.5 MW is added from hot utility to the first interval.

This does not change the heat balance within each interval, but increases all of the heat flows between intervals by 7.5 MW, giving one heat flow of just zero at an interval temperature of 145 °C.

Now heat flows cannot be negative, this is infeasible. So to make the cascade feasible what we need to do is we have to ensure that no heat flow is negative. How do I do that? By adding hot utility, so sufficient heat must be added from hot utility to make the heat flows positive or the heat flows non negative at least better or equal to 0. So the minimum amount of heat that is needed from the hot utility should be equal to the largest negative heat flow.

Because then that value will be 0 and all other values will definitely be greater than 0. So the largest negative 7.5 megawatt here. So what we will do is. We will conclude that smallest amount of heat needed from the hot utility is 7.5 megawatt. If I add 7.5 megawatt what will happen is this value will become 0 and all other will be greater than 0. So that becomes a feasible cascade.

Note that this does not change the heat balance within each interval but increases all of the heat flows between intervals by 7.5 megawatt. Giving one heat flow of just 0 at an interval of this 1 in interval character is by 145 degree Celsius.

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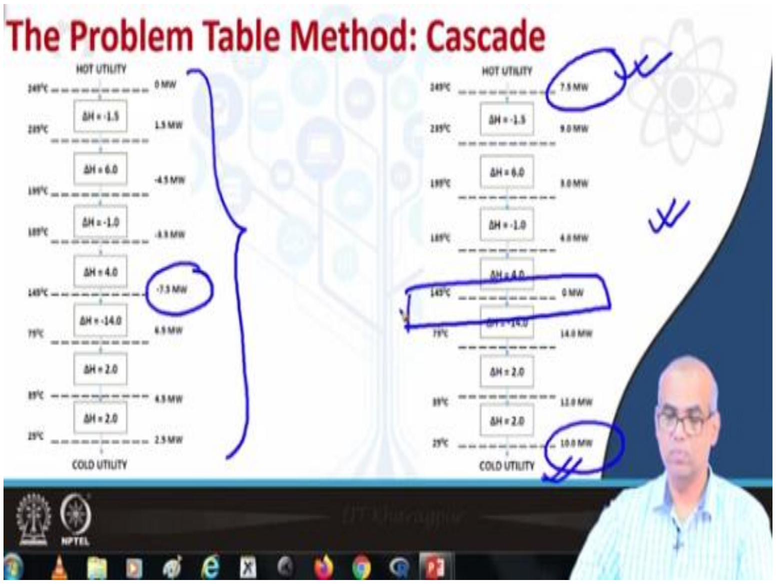

The Problem Table Method: Cascade

So this is shown here, so this was the cascade which is infeasible because some heat flows are negative then we looked at the largest negative value and add that quantity to all the heat flow values and then I obtain this cascade which is now big is feasible. So these values gives me hot utility required 7.5 megawatt and these gives me the value of cold utility that is required. Note that this is the hot utility required and this is going to be the cold utility required. Also these values give me the pinch temperature where the heat flow is 0.

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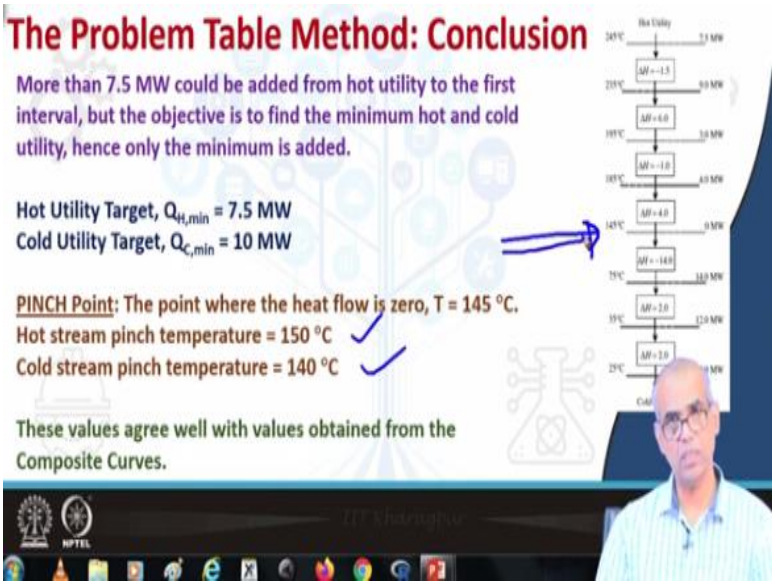

The Problem Table Method: Conclusion

More than 7.5 MW could be added from hot utility to the first interval, but the objective is to find the minimum hot and cold utility, hence only the minimum is added.

Hot Utility Target, $Q_{H,min}$ = 7.5 MW
Cold Utility Target, $Q_{C,min}$ = 10 MW

PINCH Point: The point where the heat flow is zero, T = 145 °C.
Hot stream pinch temperature = 150 °C
Cold stream pinch temperature = 140 °C

These values agree well with values obtained from the Composite Curves.

Note that we could have added more than 7.5 kilowatt or megawatt from the hot utility to the intervals. So if I add 7.5 megawatt to the first interval when I added 7.5 megawatt to this first interval. 7.5 megawatt got added to each intervals. Now I could have added from hot utility more than 7.5 megawatt. That also would have given me a feasible cascade. But since my objective is to find out the minimum hot utility that is required and minimum cold utility that is required.

I added only that much to the first interval which will make that minus 7.5 equal to 0. So hot utility target becomes 7.5 megawatt and the cold utility target is 10 megawatt. Also the pinch point or the pinch temperature is indicated by the temperature where the heat value is 0, heat flow is 0 this is 145 degree Celsius here, so the hot streams pinched temperature the actual hot stream pinch temperature will be 145 degree Celsius plus 5 degree Celsius.

Because I reduce those by delta t minimum by 2, which is 150 degrees Celsius and the cold stream pinch temperature will be 145 degree Celsius minus 5 degrees. Celsius, so 140 degree Celsius. So hot streams pitch temperature will be 145 plus 5 degree Celsius. 150 and cold streams temperature will be 145 minus 5 degree Celsius with then 140 degree Celsius. Remember that I reduce the value of hot streams to get the shifted temperature and I increase the value of cold streams temperature to get the shifted constant temperature.

So that adjustment is again being made and I obtained halt hot steam pitch temperature as 150 and cold stream pinched temperature as 140 degree Celsius. Note that these values agree well with the values that you obtain from the composite curves.

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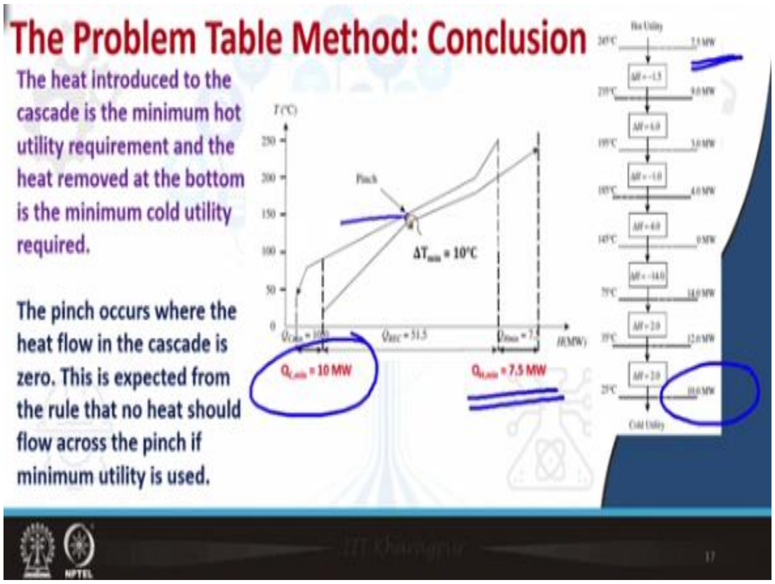

The Problem Table Method: Conclusion

The heat introduced to the cascade is the minimum hot utility requirement and the heat removed at the bottom is the minimum cold utility required.

The pinch occurs where the heat flow in the cascade is zero. This is expected from the rule that no heat should flow across the pinch if minimum utility is used.

Hot utility target 7.5 megawatt, cold utility target 10 megawatt in both the cases and also the pinch temperature. Hot stream pinch temperature and cold stream pinch temperatures. So both agrees well and it should they should agree well.

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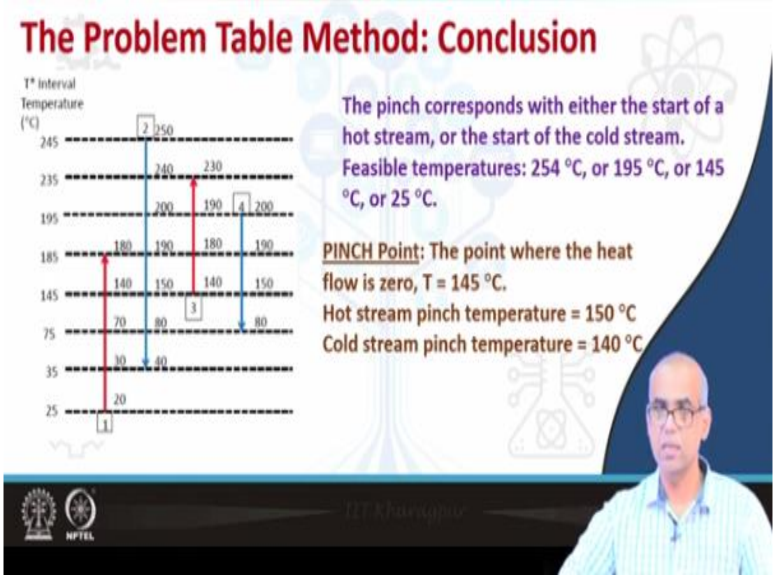

The Problem Table Method: Conclusion

The pinch corresponds with either the start of a hot stream, or the start of the cold stream. Feasible temperatures: 254 °C, or 195 °C, or 145 °C, or 25 °C.

PINCH Point: The point where the heat flow is zero, T = 145 °C.
Hot stream pinch temperature = 150 °C
Cold stream pinch temperature = 140 °C

Also would like to complete with once comment that the pinch corresponds with either the start of a hot stream or the start of a cold stream. So if I now look at that stream population table, then the candidate temperatures which can qualify for being pinched temperatures are 245 because it starts; 195 because this starts, 145 because this hot stream starts here or 25 degree Celsius because this hot stream starts here.

Note that we have obtained 145 degree Celsius, which is one of these four possibilities. So we noted that the problem table method is the numerical method which is convenient and several algorithms or softwares that are available implements this method to obtain the precious value of pinch temperature as well as minimum hot utility target, minimum cold utility target. With this we stop our discussion here.