Process Design Decisions and Project Economics

Prof. Dr. V. S. Moholkar
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Module - 5
Energy (or Heat) Integration of the Process
Lecture -23
Concepts and Basic Principles of Energy (or Heat) Integration - Part I
(Composite Curves and Delta T min)

Welcome, we will start today the fifth module of our course that is heat integration of the process. So far we have studied the protocol of design of a process. How the design evolves through several steps, the hierarchy of decisions is first that we have to decide whether we have to go for batch process or continuous process. Then we have to decide the input output structure of the flow sheet, then the recycle structure of the flow sheet, then we have to design the separation processes and finally is the heat integration of the process.

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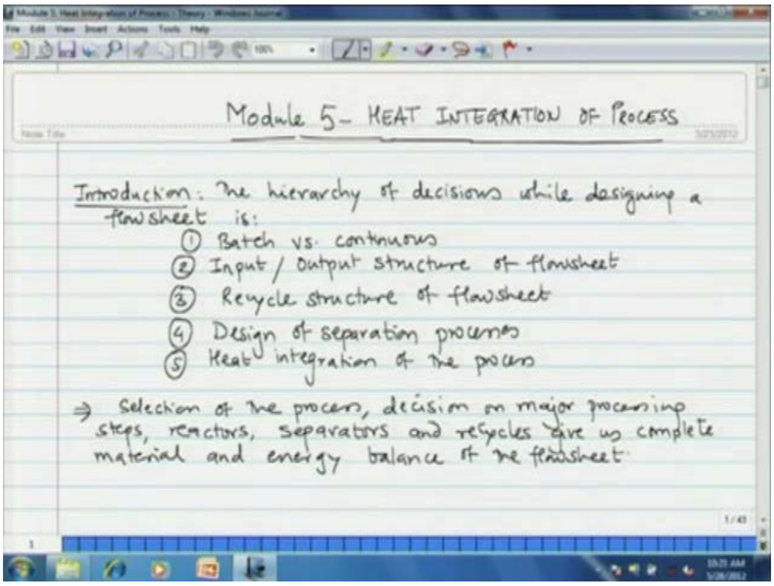

Module 5- HEAT INTEGRATION OF PROCESS

Introduction: The hierarchy of decisions while designing a flowsheet is:

① Batch vs. continuous
② Input / Output structure of flowsheet
③ Recycle structure of flowsheet
④ Design of separation processes
⑤ Heat integration of the process

⇒ Selection of the process, decision on major processing steps, reactors, separators and recycles give us complete material and energy balance of the flowsheet.

Selection of the process and decision decisions on major processing steps reactor separators and recycle steam gives us the complete energy and material balance of the flow sheet. That is if we talk about the ((Refer Time: 01:14)) type of design, the inner most ((Refer Time: 01:18)) is the reactor design, then comes the separation systems then comes the heat integration. So, the design is evolving from center to outside of the design

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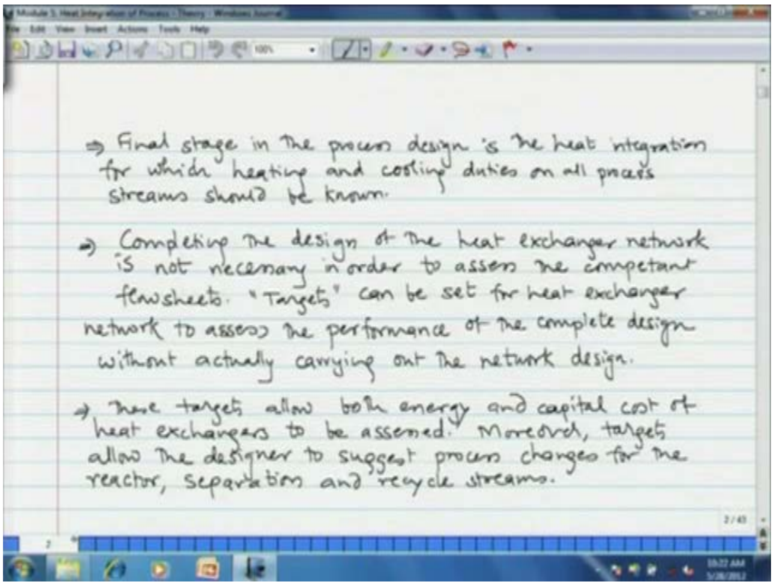

⇒ Final stage in the process design is the heat integration for which heating and cooling duties on all process streams should be known.

⇒ Completing the design of the heat exchanger network is not necessary in order to assess the competant flowsheets. "Targets" can be set for heat exchanger network to assess the performance of the complete design without actually carrying out the network design.

⇒ These targets allow both energy and capital cost of heat exchangers to be assessed. Moreover, targets allow the designer to suggest process changes for the reactor, separation and recycle streams.

Now, we have completed all the previous steps we have that data, so that is what we note that. Final stage in the process design is the heat integration for which heating and cooling duties on all process steams should be known. Then completing the design of heat integration network is not necessary in order to assess the competent flow sheets. We are still at the conceptual design means we are assessing the profitability of different flow sheets on pen and paper.

Therefore, while short listing some of the best flow sheets we do not have to design the entargeted exchanger network, we can identify the targets. So, the targets can be set for heat exchanger network to assess the performance of the complete design without actually carrying out the network design. These, targets allow us to evaluate both energy and capital cost of heat exchanger moreover the targets also allow the designer to suggest process changes for reactor separation and recycle steam.

Obviously, the goal is to minimize the energy requirement of the process as possible because energy is costly whether we have to heat or whether we have to cool we have to spend energy. So, the heat integration of the process means essentially utilizing the excess heat surplus heat at one part of the process for meeting the demands at the second part of the process where the heat is in deficit.

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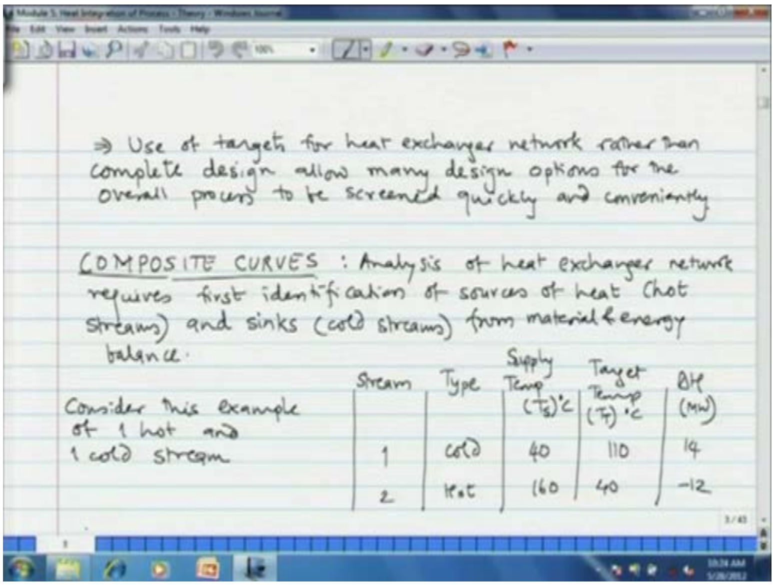

⇒ Use of targets for heat exchanger network rather than complete design allow many design options for the overall process to be screened quickly and conveniently

COMPOSITE CURVES : Analysis of heat exchanger network requires first identification of sources of heat (hot streams) and sinks (cold streams) from material & energy balance.

Consider this example of 1 hot and 1 cold stream

Stream	Type	Supply Temp (T_S) °C	Target Temp (T_T) °C	ΔH (MW)
1	cold	40	110	14
2	Hot	160	40	−12

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The use of targets for heat exchanger network rather than the complete design allow many designs for overall process to be screened quickly and conveniently. We shall see as how to identify the targets for heat exchanger network after integrating or after recovering as much heat as possible within the process some heat still needs to be supplied externally in the form of utilities, so just steam liquid. So, that is the heat requirement secondly when all of the heat is all of the excess heat is absorbed in the process itself the process terms which need to be cooled to room temperature or even below that those cause load on the cooling water requirement.

So, that also can be taken as a heating load because we have to circulate cooling water then we have to operate cooling towers to restore the temperature of cooling water so and so forth. However, as I said that we do not have to we are at a stage of screening of process alternatives. We do not have to go for a complete heat exchanger design, we have to only identify the targets that means we have to identify the minimum hot utility requirement and the minimum cold utility requirement. Now, let us see how we can do it, I am giving here an example, first of all we have to go for composite curves. The analysis of heat exchanger network requires first the identification of sources of heat hot streams and strings of it cold streams from the material and energy balance.

Now, consider the example that is appearing on the screen, now we have one hot stream and one cold stream. The supply temperature of the cold stream is 40 degrees and the target temperature is 100 and 10 degrees and heat that are available with this or the heat that needs to be supplied to this steam, this steam is 14 mega Watts. Then we have another hot screen which is available at 160 degrees and the target temperature it needs to be cooled in 40 degrees. It has minus 12 mega volt that is minus indicate surplus or plus indicate deficit, so minus 12 mega Watts of heat available. Now, we have to absorb as much heat from the hot stream into the cold stream as possible.

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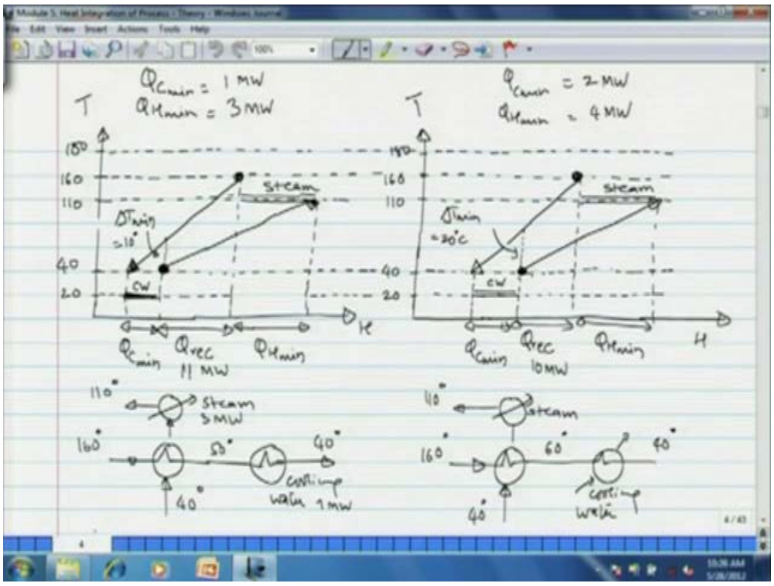

How we can achieve that, for that purpose we plot the two steams on an H T diagram which means on the x axis, we plot enthalpy and y axis we plot temperature. So, on the screen you see, now the two steams the hot stream is available at 160 degrees it is getting cooled to 40 degrees. Then the cold stream is available at 20 degrees and it is getting cool heated to 100 and 10 degrees. Let us see, now how you can do it, now I am plotting the two curves and that you see on the screen, now below here you will see the same steams plotted in the form of flow sheet.

Now, we have to decide the minimum if these two teams are contacted in heat exchanger what should be the delta T min at any end of the heat exchanger. We know from basic heat exchanger theory that the area of the heat exchanger is proportional to, sorry inversely proportional to the overall heat transfer coefficient and the L M T D the delta T min. So, we have the relation Q is equal to u a delta T min for a given heat duty Q the area of heat exchanger is Q divided by u into delta T min. Now, the delta T min we set two as a minimum, so we assume that the minimum delta T min at any end of the heat exchanger should be about 10 degrees. Now, this 10 degree has come out of experience it is an empirical value.

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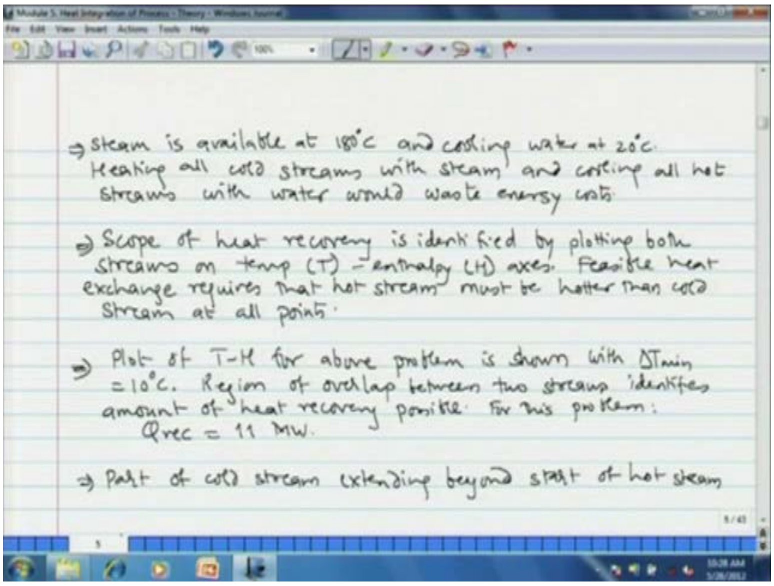

⇒ steam is available at 180°C and cooling water at 20°C. Heating all cold streams with steam and cooling all hot streams with water would waste energy costs.

⇒ Scope of heat recovery is identified by plotting both streams on temp (T) – enthalpy (H) axes. Feasible heat exchange requires that hot stream must be hotter than cold stream at all points.

⇒ Plot of T-H for above problem is shown with $\Delta T_{min} = 10°C$. Region of overlap between two streams identifies amount of heat recovery possible. For this problem:
$Q_{rec} = 11$ MW.

⇒ Part of cold stream extending beyond start of hot steam

So, we have the hot utility steam available at 180 degree and cooling water at 120 degrees then heating all cold streams with steam and cooling with all hot streams with water would be waste of energy. So, we have to see as much coupling between the hot and cold stream that we are given as possible, so that the load on steam and cooling water reduces. Now, the scope of heat recovery is identified by plotting both the steams on the diagram that I just said and then we set delta T minimum at any end of the heat exchanger were as 10 degrees.

Then, you can see that the reason of overlap between the two curves gives us the amount of heat that could be recovered and for delta T minimum equal to 10 degree centigrade. We have a heat recovery of 11 mega Watts, we have a heat recovery of 11 mega Watts, but despite this even after recovering you see how much heat was available with hot stream. It was 12 mega Watts, how much heat was to be was required for heating the cold stream of 14 mega Watts out of which 11 mega Watts is coming from the coupling between the two steams.

This leaves 3 mega Watts to be supplied to the cold stream to meet the 14 mega Watt demand and the hot stream is still left with 1 mega Watt of energy. Now, these two could be these two energy requirements could be met with steam and cooling water as I am showing here the hot stream. The cold stream after absorbing 11 mega Watts from hot stream is still left with 3 mega Watt.

So, that is supplied by steam the cold stream after taking the hot stream the hot stream after giving 11 mega Watts to the cold stream is still left with 1 mega Watt and that could be taken out using cooling water. Now, this delta T minimum was an empirical value as I said now how we can see the effect of this particular empirical parameter.

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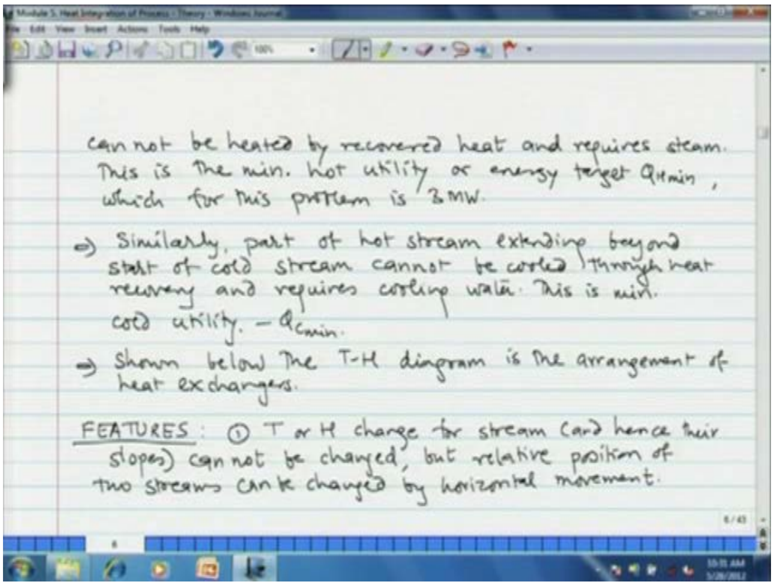
can not be heated by recovered heat and requires steam. This is the min. hot utility or energy target Q_{Hmin}, which for this problem is 3 MW.

⇒ Similarly, part of hot stream extending beyond start of cold stream cannot be cooled through heat recovery and requires cooling water. This is min. cold utility. – Q_{Cmin}.

⇒ Shown below the T-H diagram is the arrangement of heat exchangers.

FEATURES : ① T or H change for stream (and hence their slopes) can not be changed, but relative position of two streams can be changed by horizontal movement.

Suppose, we change the delta T minimum to 20 degrees, now how we can do that this we can do by shifting the curves horizontally we can change the enthalpy, we can change the relative enthalpy by shifting the curves horizontally. Then in the second graph which is now shown the right hand side of the screen we have delta T minimum is 20 degrees. Now, after you shift the cold curve on to right hand side that decreases the overlap between the two lines.

The two streams here the Q recovery or the heat that is recovered through the coupling of the two streams is reduced from 11 mega Watt to 10 mega Watt, when we have delta T minimum equal to 20 degrees. Then this is this particular feature leaves 4 mega Watt deficit with the cold stream which has to be met with steam and 2 mega Watts of excess with hot stream which has to be taken out using cooling water.

So, if you compare these values that Q c min in case of delta T min minimum equal to 10 degrees and Q H min minimum hot utility for delta T min equal to 20 degrees and you see that as delta T minimum value increases the load on the utilities also increases. So, that point I have noted here the features e temperature or enthalpy change for stream and hence their slopes that cannot be changed, but relative position of the streams can be changed by horizontal movement.

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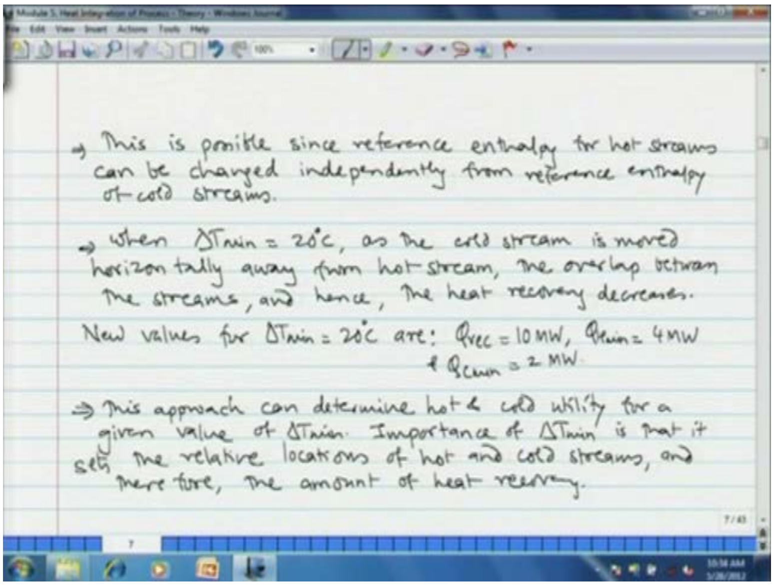

→ This is possible since reference enthalpy for hot streams can be changed independently from reference enthalpy of cold streams.

→ When $\Delta T_{min} = 20°C$, as the cold stream is moved horizontally away from hot stream, the overlap between the streams, and hence, the heat recovery decreases.

New values for $\Delta T_{min} = 20°C$ are: $Q_{rec} = 10\ MW$, $Q_{Hmin} = 4\ MW$ & $Q_{Cmin} = 2\ MW$.

⇒ This approach can determine hot & cold utility for a given value of ΔT_{min}. Importance of ΔT_{min} is that it sets the relative locations of hot and cold streams, and therefore, the amount of heat recovery.

This is possible since the reference enthalpy for hot streams can be changed independently from the reference enthalpy of the cold streams when delta T minimum equal to 20 degrees as the cold stream is moved horizontally away from the hot stream the overlap between the streams. Hence, the heat recovery decreases the new values for delta minimum 20 degrees are Q c, Q recovery equal to 10 mega Watt Q H min equal to 4 mega Watt. Q c min equal to 2 mega Watt, the minimum cold utility Q c min is equal to minimum cold utility q H min is minimum hot utility and the values are 2 and 4 mega Watt respectively.

This approach can determine the hot and cold utility for a given value of delta T min importance of the delta T mini delta T minimum is that it sets the relative locations of the hot and cold streams. Therefore, the amount of heat recovery, Let us extend the same theme for multiple streams.

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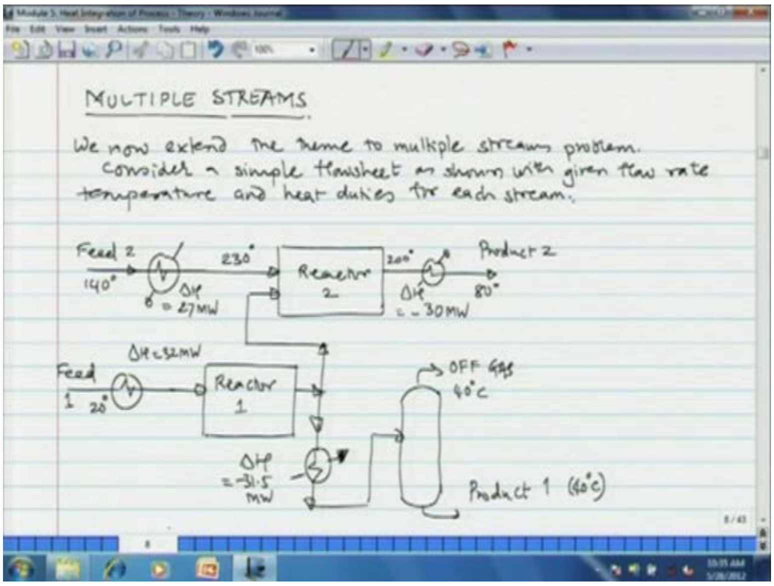

MULTIPLE STREAMS

We now extend the theme to multiple streams problem. Consider a simple flowsheet as shown with given flow rate temperature and heat duties for each stream.

Now, we shall have two hot streams and two cold streams and then we shall see how we can couple the streams to have as maximum heat recovery as possible for a given delta T minimum. Now, what you see on the screen is a simple process, we have two reactors with feeds feed 1 is at enters at 20 degrees and it is heated to 180 degrees. Then, the feed 1 enters at 20 degrees and is heated to 180 degrees to reactor 1 so that requires 32 mega Watt of energy feed the feed for reactor 2 is at 140 degrees. It needs to be heated to 230 degrees for entering the reactor, so that delta H is the heat requirement is 87 mega Watt the output of reactor 1 also enters reactor 2 part is sent to reactor 2 and part is sent for separation and the product of reactor 2 is comes out at 200 degrees. It has to be cooled to 80 degrees, so it gives out about 30 mega Watts of heat. The product of reactor 1 is splitting in two parts as I just said one part goes to reactor 2 another part is cooled and that gives out 31.5 mega Watt of heat.

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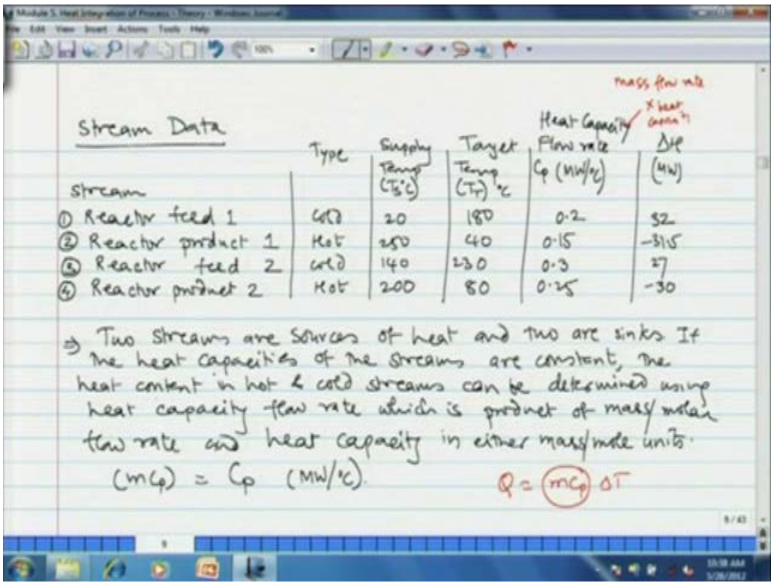

Stream Data

mass flow rate × heat capacity

Stream	Type	Supply Temp (T_S °C)	Target Temp (T_T) °C	Heat Capacity Flow rate C_p (MW/°C)	ΔH (MW)
① Reactor feed 1	cold	20	180	0.2	32
② Reactor product 1	Hot	250	40	0.15	−31.5
③ Reactor feed 2	cold	140	230	0.3	27
④ Reactor product 2	Hot	200	80	0.25	−30

⇒ Two streams are sources of heat and two are sinks If the heat capacities of the streams are constant, the heat content in hot & cold streams can be determined using heat capacity flow rate which is product of mass/molar flow rate and heat capacity in either mass/mole units.

$(mC_p) = C_p$ (MW/°C).

$Q = \boxed{mC_p} \Delta T$

So, we have essentially two hot streams and two cold streams reactor feed 1 cold stream supply temperature 20 degrees target temperature 180 degrees heat capacity flow rate. Now, heat capacity flow rate essentially mass rate into heat capacity mass or molar flow rate that depends and the corresponding heat capacity. So, this is because we have the basic relation Q is equal to m c p delta T and here we are coupling the m into c p, so as to get the heat capacity flow rate. So, m into c p is the flow rate capacity and the units of that as mega Watt per degree centigrade.

Now, m value you can define either in molls or mass, so c p will also correspondingly in either mol per degrees like the joules per molls degree Kelvin or Joules per kg per degree Kelvin depending on what you need for them. But for heat capacity flow rate will always have units of mega Watt per degree centigrade or mega Watt per Kelvin depending on the units that you need. So, we have the stream data is given reactor product one is a hot stream supply temperature 250 target temperature 40 heat capacity flow rate 0.15.

So, it gives out minus 31.5 mega Watt of heat reactor feed 2 is a cold stream and reactor product two is a hot stream. So, that has energy requirement of 27 mega Watt and energy surplus of 30 mega Watts each. The two sources are the two streams are sources of heat and two are sinks if the heat capacities of the streams are constant the heat content in the hot and cold stream can be determined using the heat capacity flow rate which is a product of mass molar flow rate as I just said.

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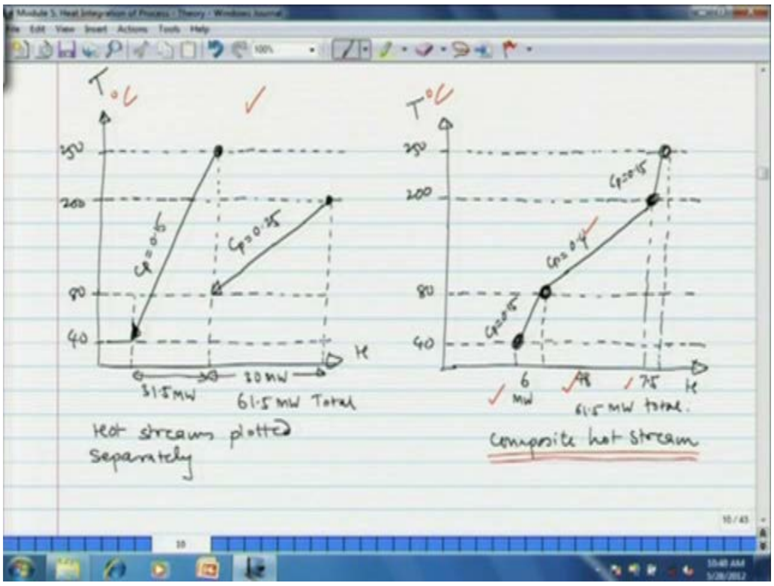

Now, what wee plot are hot streams the left hand side plot this plot use the H T diagram for the two hot streams and these hot streams are plotted separately one stream goes from 250 to 40. Second stream goes from 200 to 80, 31.5 mega Watt of surplus with first stream 30 mega Watt with second.

Now, these two streams can be combined to form a composite hot stream here what will happen is that temperatures will remain the same. But c p values will get added like for example, in the temperature interval of 80 to 200 will have two streams because the stream one is going from 40 to 250. So, it is available in the temperature interval of 80 to 200. So, in this particular temperature interval the two streams are available, so they add together and the total c p for that is 0.4 between 40 to 80 interval, temperature interval 40 to 80 degree centigrade.

We have the c p only one stream the c p 0.5 and above 200 degree again we have only the first stream. So, there c p is on front and then we can have a composite H T diagram which gives us the available heat in a particular temperature interval. For example, between 40 to 80, we have total 6 mega Watts of heat available between 80 to 200 we have 48 mega Watts of heat available and from 200 to 250 we have 7.5 mega Watt of heat available so that adds up totally 261.5 mega Watt.

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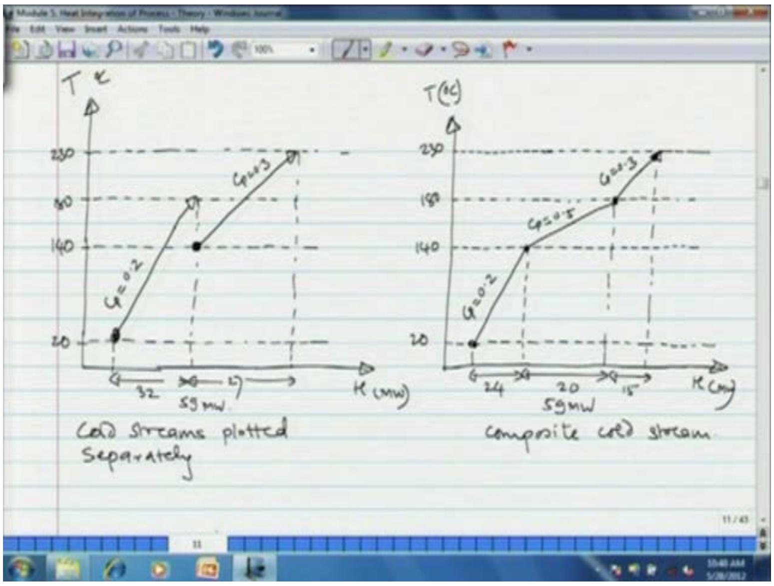

Similarly, we can do for cold streams also what you see on the left hand side is the individual plot the two cold streams plotted separately, the first stream going from 20 to 180, second stream going from 140 to 230. Now, in a similar way we find that in the temperature interval 140 to 180 both streams are present. So, when we make a composite diagram of the cold streams, we can see that between 20 to 140 only first stream is available. So, c p 0.2 between 140 to 180 two streams are available, so their heat capacity flow rates get added and then we have c p equal to 0.5. Then after 180 degrees again we have first stream that is c p equal to 0.3. So, this gives us again distribution of heat requirement against temperature interval between temperature intervals 20 to 140. We need 24 mega Watt between 140 to 180 we need 20 mega Watt and 180 to 230 we need 15 mega Watts.

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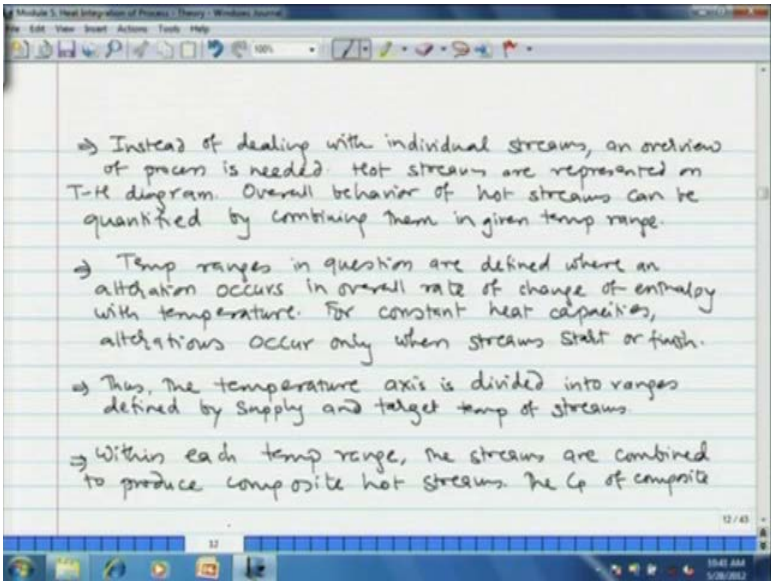

⇒ Instead of dealing with individual streams, an overview of process is needed. Hot streams are represented on T-H diagram. Overall behavior of hot streams can be quantified by combining them in given temp range.

⇒ Temp ranges in question are defined where an alteration occurs in overall rate of change of enthalpy with temperature. For constant heat capacities, alterations occur only when streams start or finish.

⇒ Thus, the temperature axis is divided into ranges defined by supply and target temp of streams.

⇒ Within each temp range, the streams are combined to produce composite hot streams. The Cp of composite

So, the composite diagrams gives us an overview of the process hot streams are the overall behavior of the hot streams can be quantified by combining them together in the given temperature range. All this points which I just said I have noted in this slide the temperature ranges in question are defined where an alteration occurs in overall rate of change of enthalpy which temperature for constant heat capacities alterations occur only when stream start or finish. Thus, the temperature axis is divided into ranges defined by supply and target temperature of streams within each temperature range the streams are combined to produce the composite hot streams.

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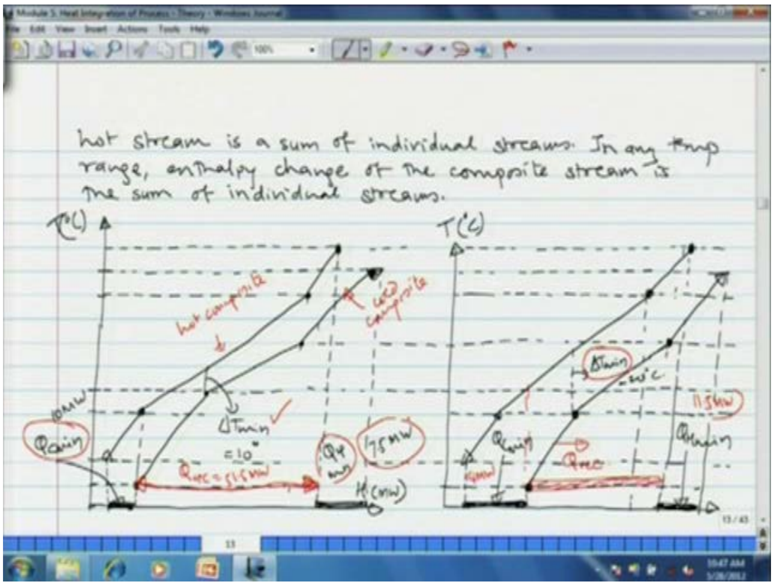

hot stream is a sum of individual streams. In any temp range, enthalpy change of the composite stream is the sum of individual streams.

The c p of composite hot streams is a sum of individual streams in any temperature range the enthalpy change of the two of the composite streams is the sum of individual streams. Now, what we see here is the two composite streams plotted together and the same diagram. Now, this is the hot composite stream and the lower one is cold composite stream and these are plotted on the same H T diagram. Now, we will see that for delta T min is equal to 10 degrees the region of overlap between the two streams which is essentially the heat recovery the one which I am marking.

Now, is 51.5 mega Watt Q recovery is 51.5 Watt, now we shall calculate these values later for time being I am just giving you the direct answer, but we are going to treat the same problem later and then we shall actually calculate these values. The after meeting 51.5 mega Watts of heat recovery, we have the cold streams left with energy requirement of 7.5 mega Watt which I am marking. Now, the hot composite curve extends beyond, sorry the cold composite curve extend beyond the hot composite curves to this much extend which I am marking and this is the minimum hot utility requirement Q H min this is this 7.5 mega Watt.

Now, the part of hot composite curves that extends beyond the cold composite curve which is already marked here, I have written here Q c min that is the minimum cold utility requirement and this turns out to be 10 mega Watt. So, we have both complete heat exchanger network target available here. We have Q recovery, Q recovery ranging in this ray the one the marked the arrows in red that is the region of recovery that is 51.5 mega Watt after this heat recovery we are left with 7.5 recovery of heat requirement for cold streams that is met with hot utility.

So, that is Q H min and after this heat recovery we are left with ten mega Watt of excess heat with hot composite curves which is taken off from cold streams, so that is what the overall energy target is. Now, as we did in the previous case we can change the delta T min delta T min here was assumed to be 10 degrees, we can change delta T min to 20 degrees by shifting this curve the cold composite curve horizontally to right. Now, what will happen, obviously the region of heat recovery will go down the heat recovery in this now is only in this range the one that is marked red. So, this is the region of heat recovery, Q recovery which is which has now reduced this region has released.

Therefore, a lot of heat requirement is left out the amount of heat that needs to be supplied to the cold streams through hot utility is now 11.5 mega Watt. Now, this again values we are going to calculate, so the Q H min increases from 7.5 mega Watt to 11.5 mega Watt. Then the Q c min lot of heat remains in the hot composite stream after absorption into the cold stream and then the Q c min is now 40 mega Watt. So, that is how the picture changes with increasing delta T min with the load on hot utility and cold utility changes, so all those points I have noted here.

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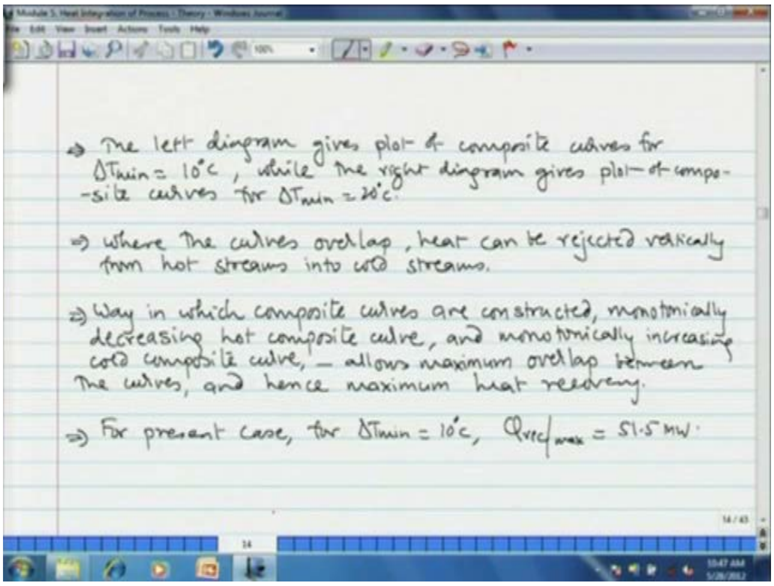

⇒ The left diagram gives plot of composite curves for $\Delta T_{min} = 10^\circ C$, while the right diagram gives plot of composite curves for $\Delta T_{min} = 20^\circ C$.

⇒ Where the curves overlap, heat can be rejected vertically from hot streams into cold streams.

⇒ Way in which composite curves are constructed, monotonically decreasing hot composite curve, and monotonically increasing cold composite curve, — allows maximum overlap between the curves, and hence maximum heat recovery.

⇒ For present case, for $\Delta T_{min} = 10^\circ C$, $Q_{rec}|_{max} = 51.5$ MW.

The left diagram gives plot of composite curves for delta T min equal to 10 degrees while the right diagram gives plot of composite curves for delta T min equal to 20 degrees where the curves overlap. The heat can be rejected vertically from hot streams into the cold streams the way in which composite curves are constructed monotonically increasing hot composite curve. Monotonically decreasing cold composite curve allows maximum overlap between the curves. Hence, the maximum heat recovery for delta T min equal to 10 degrees Q c, Q recovery is 51.5 mega Watt.

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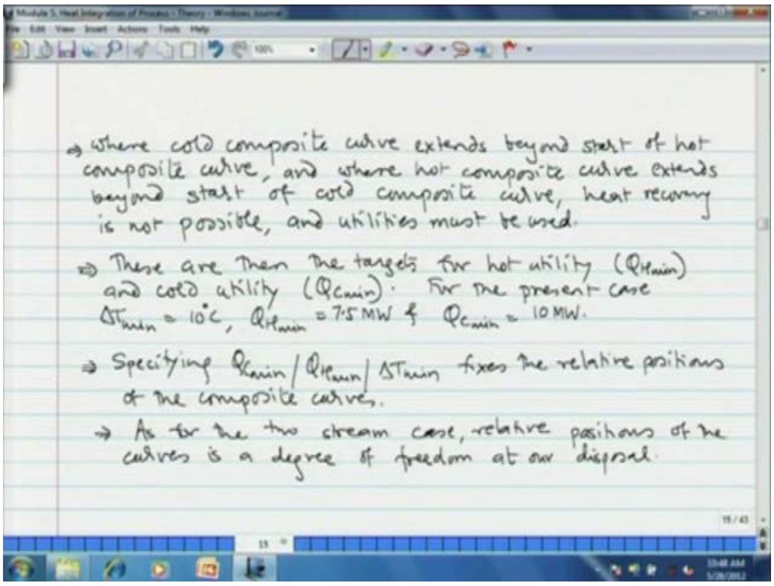

⇒ Where cold composite curve extends beyond start of hot composite curve, and where hot composite curve extends beyond start of cold composite curve, heat recovery is not possible, and utilities must be used.

⇒ These are then the targets for hot utility ($Q_{H_{min}}$) and cold utility ($Q_{C_{min}}$). For the present case $\Delta T_{min} = 10^\circ C$, $Q_{H_{min}} = 7.5$ MW & $Q_{C_{min}} = 10$ MW.

⇒ Specifying $Q_{C_{min}} / Q_{H_{min}} / \Delta T_{min}$ fixes the relative positions of the composite curves.

→ As for the two stream case, relative positions of the curves is a degree of freedom at our disposal.

When the composite curve extends beyond the start of hot composite curve and where the hot composite curve extends beyond the start of cold composite curve. The heat recovery is not possible and utilities must be used and then for delta T min equal to 10 degrees the minimum hot utility is 7.5 mega Watt and minimum cold utility is 10 mega Watt.

Now, there are three variables here Q c min Q H min delta T min specify any of the three variables fixes the relative positions of the composite curves, but usually delta T min is used as a variable rather than Q c min and Q H min. But depending on situation either you can also specify Q c min or Q H min and then that fixes both any fixing any of these three variable fixes the other two variables. So, as per as two stream cases concern the relative position of the curves also degree of freedom at our disposal.

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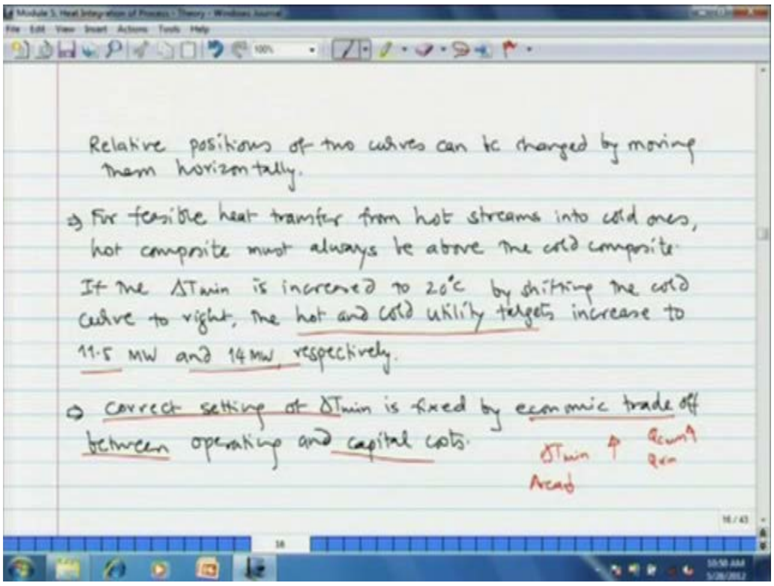

Relative positions of two curves can be changed by moving them horizontally.

⇒ For feasible heat transfer from hot streams into cold ones, hot composite must always be above the cold composite.

If the ΔT_{min} is increased to 20°C by shifting the cold curve to right, the hot and cold utility targets increase to 11.5 MW and 14 MW, respectively.

⇒ Correct setting of ΔT_{min} is fixed by economic trade off between operating and capital costs.

$\Delta T_{min} \uparrow$ $Q_{cmin}\uparrow$ Q_{Hm}

Area↓

The relative positions of the two curves can be changed by moving them horizontally for feasible heat transfer from hot streams into cold streams, hot composite curves must always be above the cold composite curve. If the delta T min is increased to 20 degrees by shifting the cold curve to right the hot and cold utility targets increase to 11.5 mega Watt and 14 mega Watt respectively.

Now, correct setting of delta T min is fixed by the economic tradeoff between operating and capital cost obviously if delta T min increases the Q c min and Q H min increase, but the area of individual heat exchanger reduces the area of heat exchangers in which the hot and cold streams are coupled. So, Q c min and Q H min indicate basically the operating cost and delta T min indicates the fixed or capital cost delta T min increases area decreases capital cost decreases. But at the same time Q c min and Q H min increase which means the operating cost decreases. So, there has to be an economic trade off for deciding the optimum level of delta T min.

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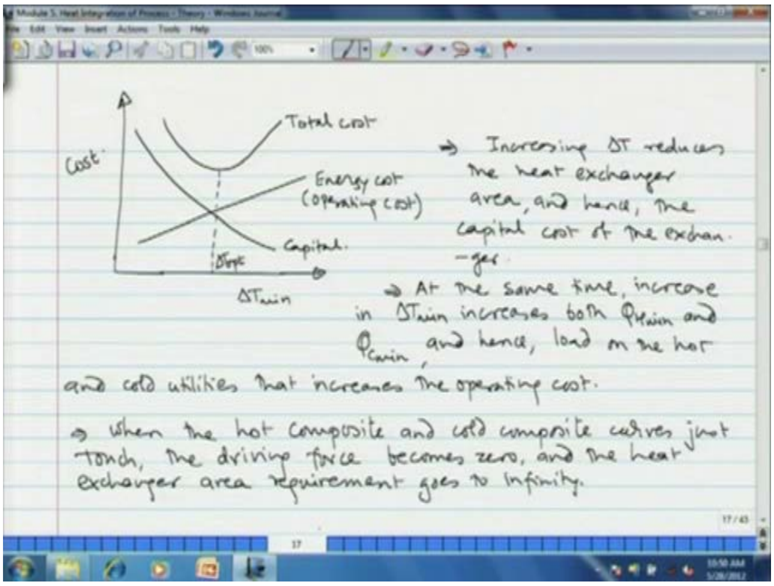

⇒ Increasing ΔT reduces the heat exchanger area, and hence, the capital cost of the exchanger.

⇒ At the same time, increase in ΔT_{min} increases both Q_{Hmin} and Q_{Cmin}, and hence, load on the hot and cold utilities that increases the operating cost.

⇒ When the hot composite and cold composite curves just touch, the driving force becomes zero, and the heat exchanger area requirement goes to infinity.

So, that is what is plotted here increasing delta T reduces the heat exchanger area. Hence, the capital cost of the exchanger at the same time increase in delta T min increases both Q H min and Q c min. Hence, the load on cold and hot utilities that increases the operating cost when the hot composite and the cold composite curves just touch then the driving force becomes 0 and the heat exchanger area requirement goes to infinity.

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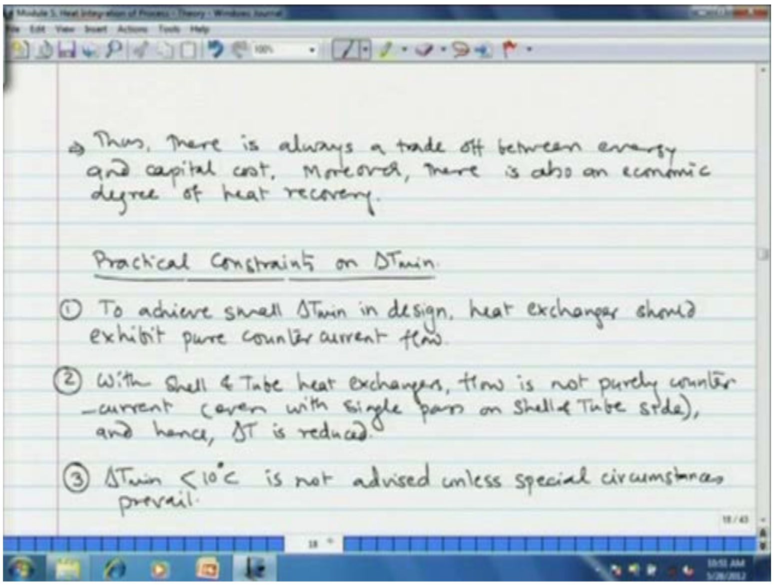

⇒ Thus, there is always a trade off between energy and capital cost. Moreover, there is also an economic degree of heat recovery.

Practical Constraints on ΔT_{min}

① To achieve small ΔT_{min} in design, heat exchanger should exhibit pure counter current flow.

② With Shell & Tube heat exchangers, flow is not purely counter-current (even with single pass on Shell & Tube side), and hence, ΔT is reduced.

③ $\Delta T_{min} < 10°C$ is not advised unless special circumstances prevail.

Thus, there is always a tradeoff between energy and capital cost, so you can see here that the total goes through a minimum at delta T min at with respect to delta T min. There is always a delta T optimum your experience tells that delta T minimum is 10 degrees for 70 heat exchangers, but for other exchangers other type of the here could be the this, this could vary, so that thing you see on the screen.

Now, that is also an economic degree of heat recovery we cannot go there are some constants where which restrict the amount of heat that could be recovered between hot and cold steps. So, the practical constraints on delta T min are to achieve small delta T min in design heat exchanger should exhibit pure counter current flow. That is a basic aspect that we have learnt in heat transfer process with shell and tube exchanger time is not purely counter current even with shell and pass on shell and tube side. So, the delta T is reduced delta T min less than ten degrees is not advised unless special circumstances prevail.

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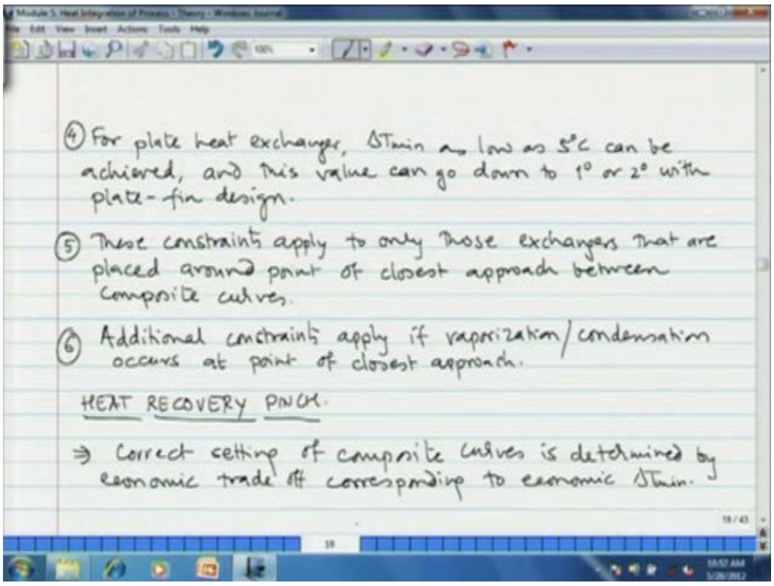

④ For plate heat exchanger, ΔT_{min} as low as 5°C can be achieved, and this value can go down to 1° or 2° with plate-fin design.

⑤ These constraints apply to only those exchangers that are placed around point of closest approach between composite curves.

⑥ Additional constraints apply if vaporization / condensation occurs at point of closest approach.

HEAT RECOVERY PINCH.

⇒ Correct setting of composite curves is determined by economic trade off corresponding to economic ΔT_{min}.

For plate heat exchangers delta T min as low as 5 degrees could be possible or could be achieved and this value can go down to 1 or 2 degrees with plate and fin design. These constraints apply to only those exchangers that are placed around the point of closest approach between composite curves. Remember, that these constants apply this; we shall come back again when we study the pinch technology additional constraints apply if vaporization condensation occurs at the point of closest approach. Now, the heat recovery pinch correct setting of composite curves is determined by economic tradeoff between the corresponding tradeoff corresponding to economic delta T min.

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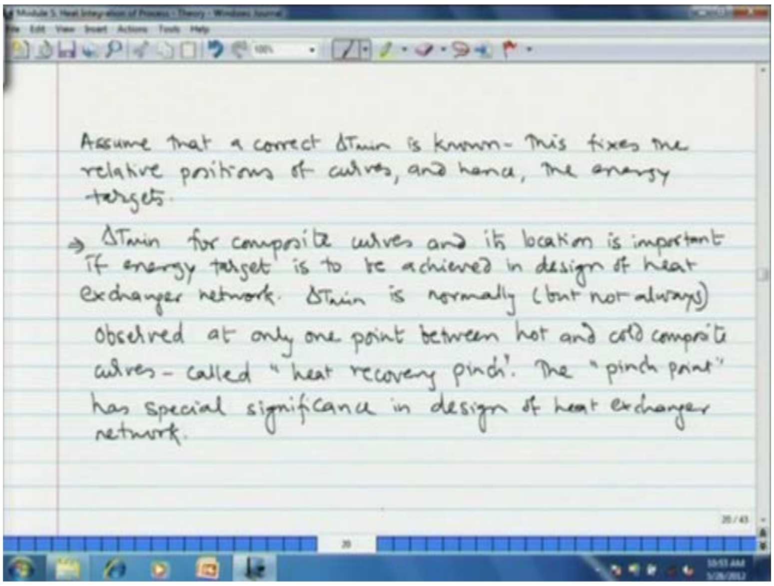

Assume that a correct ΔT_{min} is known - This fixes the relative positions of curves, and hence, the energy targets.

⇒ ΔT_{min} for composite curves and its location is important if energy target is to be achieved in design of heat exchanger network. ΔT_{min} is normally (but not always) observed at only one point between hot and cold composite curves - called "heat recovery pinch". The "pinch point" has special significance in design of heat exchanger network.

Assume that a correct delta T min is assumed and this fixes the relative positions of the curves. Hence, the energy targets the delta T min for composite curves and its location is important if the energy target is to be achieved in design of heat exchanger network delta T min is normally, but not always observed at only one point between the hot and cold composite curves called as the heat recovery pinch. The pinch point has the special significance in the design of heat exchanger network. We shall come back to this point again as I said when we shall study the pinch technology of heat exchanger network design.

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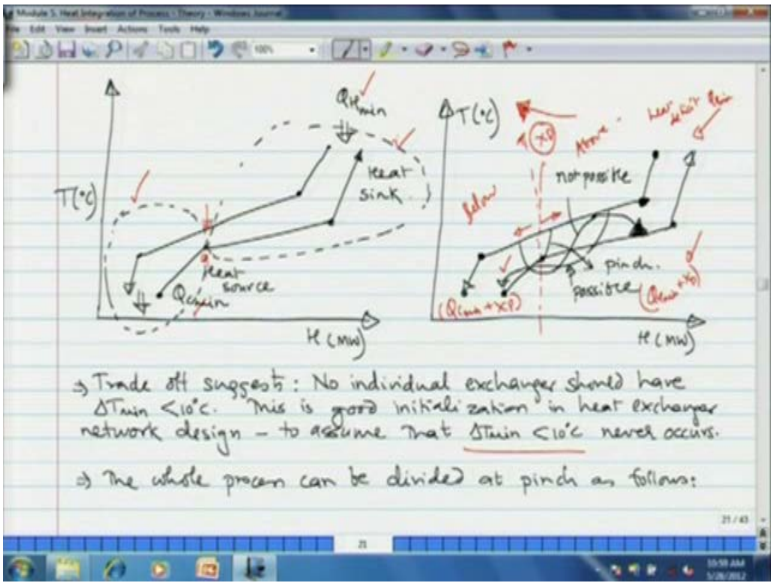

⇒ Trade off suggests: No individual exchanger should have $\Delta T_{min} < 10°C$. This is good initialization in heat exchanger network design – to assume that $\Delta T_{min} < 10°C$ never occurs.

⇒ The whole process can be divided at pinch as follows:

How we can design the coupling of the streams, so has to have maximum heat recovery. Now, the trade off suggests that no individual exchanger should have the delta T min less than 10 degrees. Now, this is the good initialization in heat exchanger network design assume that delta T min less than 10 degrees never occurs the whole process can be divided at pinch where the two curves are closest. So, this point is the pinch point where the delta T min is 10 degrees, so the whole process can be divided at pinch as follows one is the below pinch this portion, this envelop and above pinch which is this envelop.

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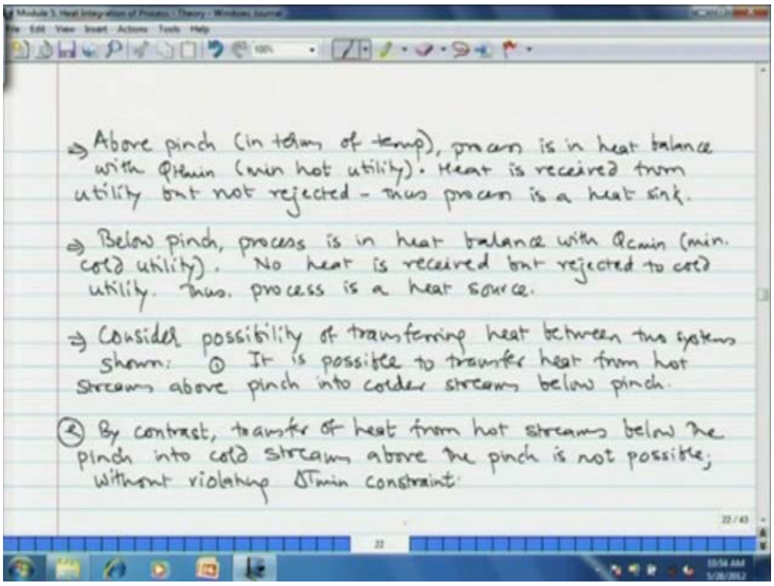

⇒ Above pinch (in terms of temp), process is in heat balance with $Q_{H_{min}}$ (min hot utility). Heat is received from utility but not rejected – thus process is a heat sink.

⇒ Below pinch, process is in heat balance with $Q_{C_{min}}$ (min. cold utility). No heat is received but rejected to cold utility. Thus process is a heat source.

⇒ Consider possibility of transferring heat between the systems shown: ① It is possible to transfer heat from hot streams above pinch into colder streams below pinch.

② By contrast, transfer of heat from hot streams below the pinch into cold stream above the pinch is not possible; without violating ΔT_{min} constraint.

Above pinch in terms of temperature the process is in heat balance with Q H min that is minimum hot utility the heat is received from the utility, but it is not rejected. Thus, a process is a heat sink above pinch which means in this region above pinch is this region here. The process is heat sink because heat is been absorbed from the hot utility that is Q H min, but not rejected below pinch process in a heat balance with Q c min or minimum cold utility no heat is recovered, but rejected to cold utility.

Thus, the process is a heat source here we are not absorbing any heat from outside, but only rejecting the heat to cold utility Q c min. So, the process is heat source consider possibility of transferring heat between two systems if it possible to transfer any heat from hot streams above pinch into colder streams below pinch by contrast. The transfer of heat from hot streams below pinch into cold streams above pinch is not possible without violating delta T min constraint.

So, what we see now is that suppose you want to this is the here the process is divided at the pinch. This is below pinch, this is above pinch, and if you want to pass heat from the streams above pinch to streams means hot streams above pinch to cold streams below pinch it is possible, but above is not possible. The reverse is not possible, you cannot pass this streams the heat from hot streams below pinch to the cold streams above pinch why because as you go above pinch here. Let us say the pinch occurs at delta some T the temperature here increases and the temperature here decreases. So, the delta T min constraint is highlighted as you go in a heat exchanger from one end to the another.

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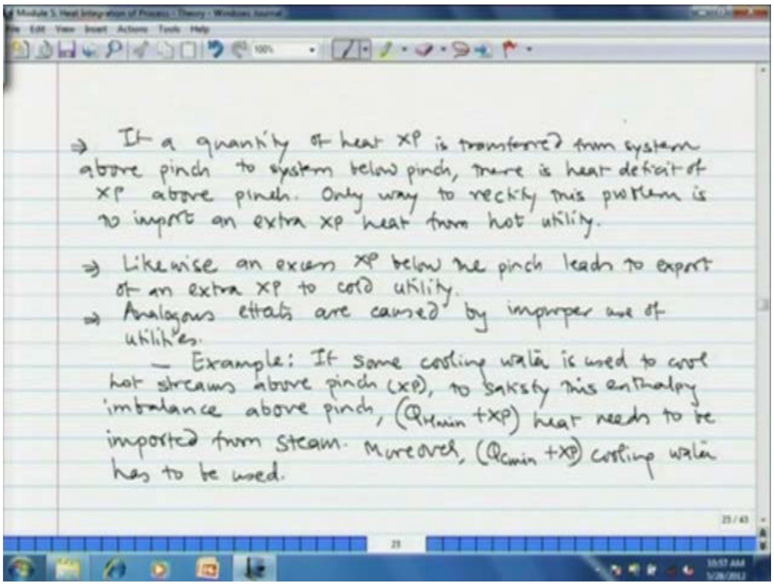

⇒ If a quantity of heat XP is transferred from system above pinch to system below pinch, there is heat deficit of XP above pinch. Only way to rectify this problem is to import an extra XP heat from hot utility.

⇒ Likewise an excess XP below the pinch leads to export of an extra XP to cold utility.

⇒ Analogous effects are caused by improper use of utilities.

— Example: If some cooling water is used to cool hot streams above pinch (XP), to satisfy this enthalpy imbalance above pinch, $(Q_{H\min} + XP)$ heat needs to be imported from steam. Moreover, $(Q_{C\min} + XP)$ cooling water has to be used.

If a quantity of heat x p is Transferred from system above pinch to system below pinch there is the heat deficit of x p above pinch the only way to rectify this problem is to import an extra x p of heat from hot utility that will increase Q H min. If you pass some heat from above pinch to below pinch streams then there will be a heat deficit here.

Then, that deficit can only be fulfilled by importing more from hot utility Q H min likewise an excess of x p below the pinch leads to export of an extra x p to cold utility analogous effects can be caused by improper use of utilities example is given here. If some cooling water is used to cool hot streams above pinch to satisfy this enthalpy importance above pinch Q H min plus x p. It needs to be imported from the steam or hot utility or moreover Q c min plus x p cooling water has to be used, so that is that is the imbalance between the processes.

If you if you give out some portion x p heat x p from above pinch to below pinch there will be heat deficit here. So, here it will be Q H min plus x p this much of heat needs to be imported from hot utility that it will just load on hot utility. Similarly, the heat that is has to be rejected to cold utility also goes up by same amount, so Q H min and Q c min both increase if you transfer heat across pinch. Therefore, when we are designing the heat exchanger network we have to see the steams above pinch, we have to see the streams below pinch. Then make a match between the two that that thing we shall come again we shall come again when we shall see the enthalpy intervals.

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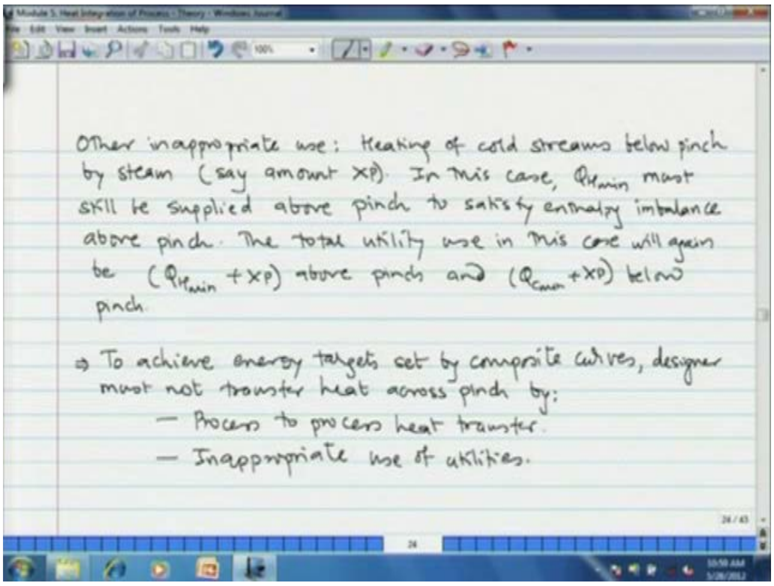

Other inappropriate use: Heating of cold streams below pinch by steam (say amount XP). In this case, $Q_{H_{min}}$ must still be supplied above pinch to satisfy enthalpy imbalance above pinch. The total utility use in this case will again be $(Q_{H_{min}} + XP)$ above pinch and $(Q_{C_{min}} + XP)$ below pinch.

⇒ To achieve energy targets set by composite curves, designer must not transfer heat across pinch by:

- Process to process heat transfer.
- Inappropriate use of utilities.

Other inappropriate use heating of cold streams below pinch by steam say by amount x p, this is one another improper use in this case the Q H min must still be supplied above pinch to satisfy enthalpy imbalance above pinch. So, the total utility in this case will again be Q H min plus x p above pinch and Q c min plus x p below pinch to achieve the energy targets set by composite curves. The designer must not transfer heat across pinch by process to process heat transfer and inappropriate use of utilities.

So, that is how that gives you the essence of the pinch the heat recovery pinch. So, the process is divided at this pinch that should not be process to process transfer across pinch where also should not be inappropriate use of utilities above and below pinch no hot utility below pinch no cold utility above pinch.

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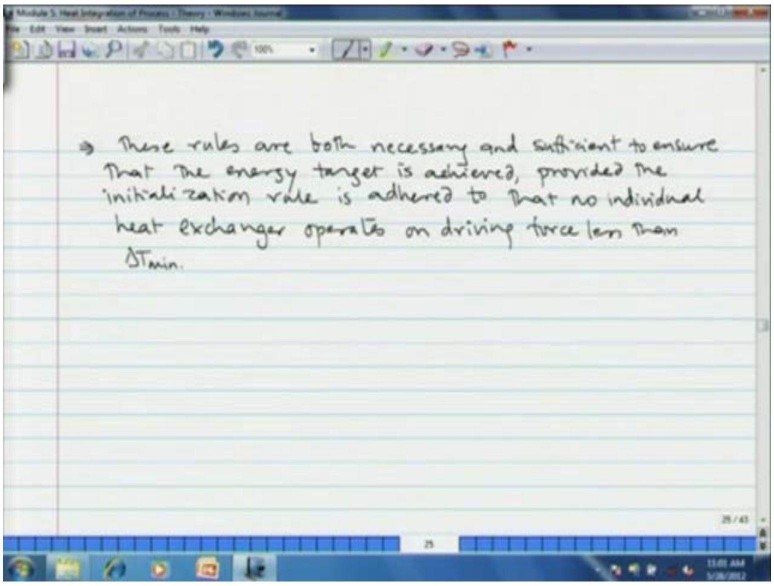

⇒ These rules are both necessary and sufficient to ensure That the energy target is achieved, provided the initialization rule is adhered to that no individual heat exchanger operates on driving force less than ΔT_{min}.

These rules are both necessary and sufficient to ensure that the energy target is achieved, provided the initialization value is adhered to that individual heat exchanger operates on driving force less than delta T min.

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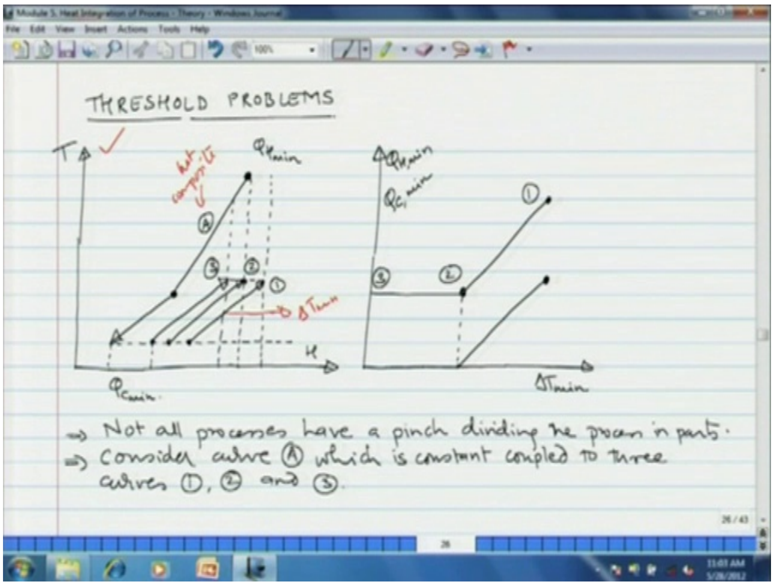

THRESHOLD PROBLEMS

⇒ Not all processes have a pinch dividing the process in parts.
⇒ Consider curve Ⓐ which is constant coupled to three curves ①, ② and ③.

So, that completes the basic theory of the heat exchange, heat recovery principle. Now, let us see some special cases like threshold problems not all of the process have a pinch dividing the process in parts consider the curve a in the figure that is shown on left hand side of the screen which is constant coupled to three curves one two and three.

Now, a is a hot composite curve and we have only one stream or let us say cold composite stream which in with constant slope and that is shown in three parts. Now, as I said you cannot move the cold composite stream horizontally that will change the delta T min. Now, initially position three now in position three you have both you have Q C min, but not Q H min.

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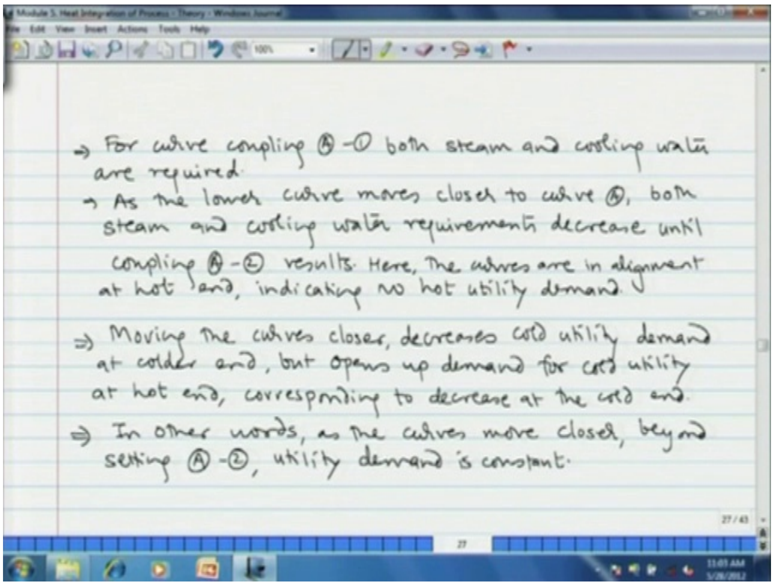

⇒ For curve coupling Ⓐ-① both steam and cooling water are required.

→ As the lower curve moves closer to curve Ⓐ, both steam and cooling water requirements decrease until coupling Ⓐ-② results. Here, the curves are in alignment at hot end, indicating no hot utility demand.

⇒ Moving the curves closer, decreases cold utility demand at colder end, but opens up demand for cold utility at hot end, corresponding to decrease at the cold end.

⇒ In other words, as the curves move closer, beyond setting Ⓐ-②, utility demand is constant.

If you couple a with one coupling A 1 coupling A 1 both steam and cooling water are required as the low curve moves closer to curve a lower curve means the cold composite curve. As the cold composite curve moves closer to curve a both steam and cooling water requirement decrease until the coupling A 2 is achieved like here A 2 coupling. Now, here you can see that a Q H min here becomes 0, because the target temperature of, sorry let the target temperature different the enthalpies are exactly matching when you have coupling A 2.

There, is no hot utility required moving the curves closer decreases the cold utility demand at the colder end, but opens up for cold utility at hot end correspondent to decrease at the cold end. So, you require cold utility both above and below pinch, you can see here that once the curve goes to for a three coupling after a three coupling even after the what you say the cold composite curve is absorbed all the heat.

There is still heat left with the hot composite curve that becomes a load on the Q c min moving the curves closer decreases cold utility demand at colder end, but opens up demand for cold utility at hot end corresponding to decrease at the cold end. In other words, as the curves move closer beyond A 2 the utility demand remains constant, so that is how is shown in this figure.

This is for case one, case two, case three to the three positions as you go beyond three positions there is no hot utility, but the cold utility demand goes up. So, here the hot stream between this temperature and this temperature the hot streams have to be cooled using cold utility. That is very strange that we are using cold utility above pinch because as I just said that you cannot use cold utility above pinch, but in this particular case you have to use because does constraint of the cold composite curve.

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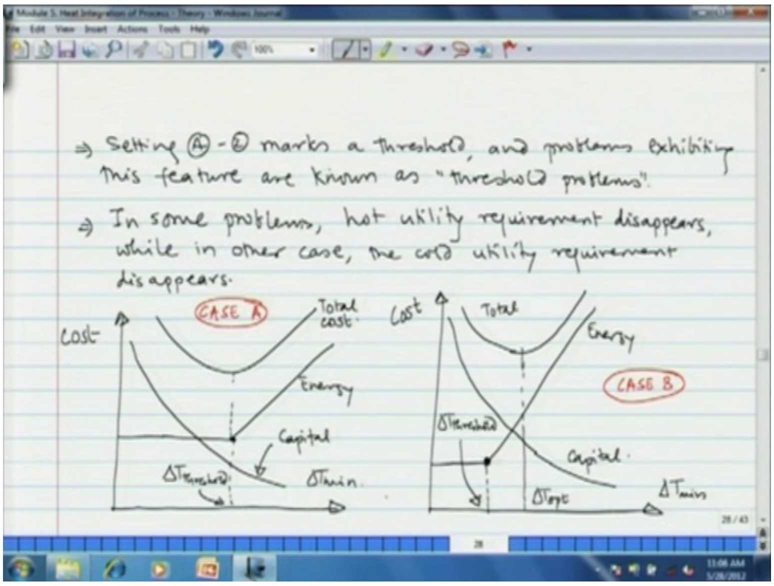

⇒ Setting Ⓐ-② marks a threshold, and problems exhibiting this feature are known as "threshold problems".

⇒ In some problems, hot utility requirement disappears, while in other case, the cold utility requirement disappears.

Setting A 2 marks threshold and a problem exhibiting this feature are known as threshold, problems in some problems hot utility requirement disappears. In some cases the cold utility requirement disappears cold utility requirement disappears. So, what I have plotted here is the cost the energy cost decreases as delta T min decreases as the second curve moves closer to the curve A. Then after delta T threshold it remains constant but the capital cost keeps on increasing as delta T min decreases the capital cost keeps on increasing.

So, from here you have an optimum whether the delta T min optimum will be the delta T threshold that depends on particular case like for example in this case in case a the T optimum and T threshold are same. But in certain cases they may not be same like the total cost may show least at some T optimum, but the threshold shows the energy requirement becomes constant and after certain delta T min a threshold. So, in this case the optimum delta T optimum as per the cost is not same as delta T threshold, but in some cases it is ok.

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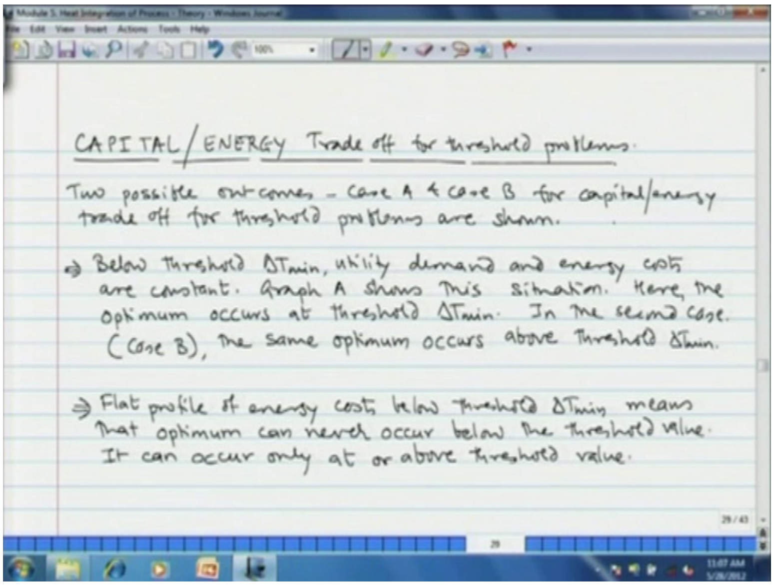

CAPITAL / ENERGY Trade off for threshold problems.

Two possible outcomes - Case A & Case B for capital/energy trade off for threshold problems are shown.

⇒ Below threshold ΔT_{min}, utility demand and energy costs are constant. Graph A shows this situation. Here, the optimum occurs at threshold ΔT_{min}. In the second case. (Case B), the same optimum occurs above threshold ΔT_{min}.

⇒ Flat profile of energy costs below threshold ΔT_{min} means that optimum can never occur below the threshold value. It can occur only at or above threshold value.

Now, let us see the capital and energy trade off for threshold problem the two possible outcomes case A and case B, which I just discussed for capital energy trade off below threshold delta T min utility demand. Energy cost is constant graph A shows this situation here the optimum occurs at threshold delta T min. In the second case, the same optimum occurs above threshold delta T min the flat profile of energy costs below threshold delta T min means that optimum can never occur below threshold value it can occur only at or above the threshold value.

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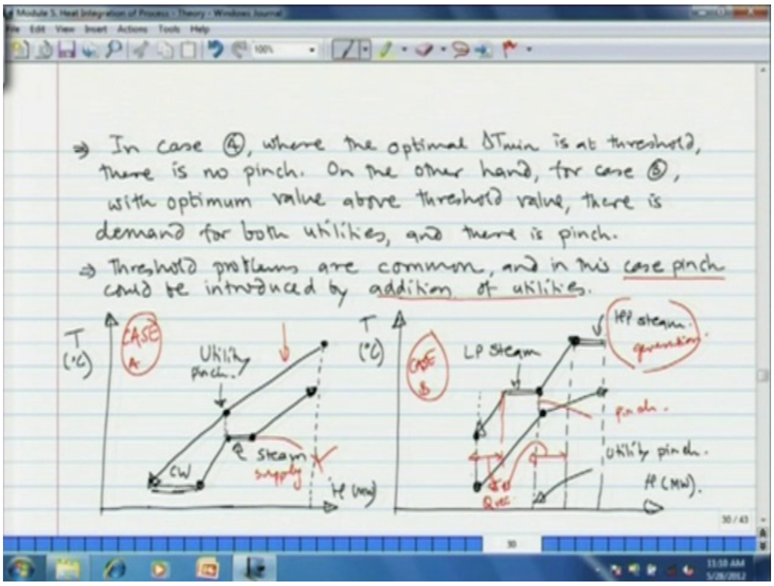

⇒ In case Ⓐ, where the optimal ΔT_{min} is at threshold, there is no pinch. On the other hand, for case Ⓑ, with optimum value above threshold value, there is demand for both utilities, and there is pinch.

⇒ Threshold problems are common, and in this case pinch could be introduced by addition of utilities.

Now, in case A where that optimum delta T min is at threshold, there is pinch. On the other hand, for case B with optimum value above threshold value there is demand for both utilities and then and there is a pinch, now threshold problems are quite common. In this case, we can introduce a pinch although when we actually plot the process curves. We absorbed no pinch, but we can introduce a pinch by addition of utilities like for example, in which case A which we have shown the hot composite curve remains the same for the cold composite curve. We divided into two parts, the first part and then here we shall have intermediate, we shall have steam generation.

Then, we have the cold utility, so that generates a pinch, another this is so likely utility addition on cold composite curve in some cases like here, sorry not steam generation means we are using steam here to keep the to heat up. The cold stream in between in some cases you can use the steam generation, so this is steam supply here we have steam generation hp steam generation here. What will happen before coupling the hot stream to the cold stream, we shall first use it for high pressure steam generation to reduce the enthalpy add constraint temperature and then in certain portion we shall couple.

Then, here we introduce the pinch and there after again we have low pressure steam generation after taking up certain heat, then we shall couple to the composite stream. So, these are the actual heat recovery areas, so these are the Q recovery areas and here we have intermediate utility generation.

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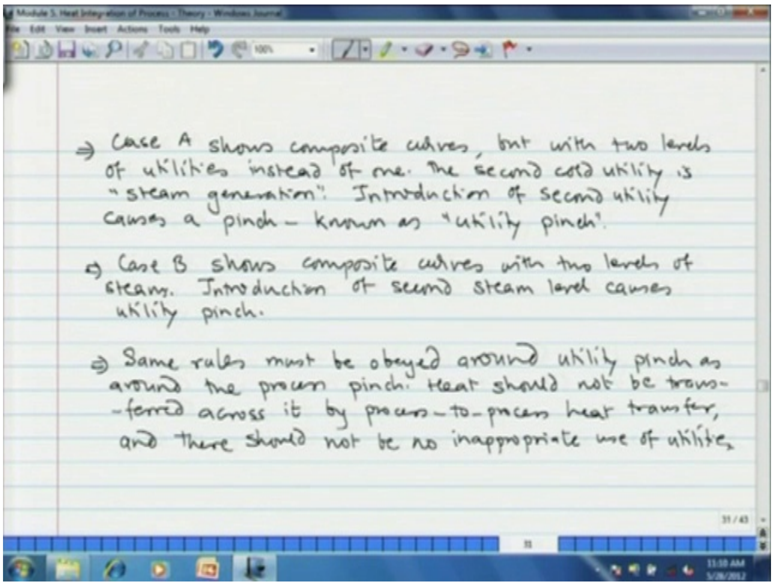

⇒ Case A shows composite curves, but with two levels of utilities instead of one. The second cold utility is "steam generation". Introduction of second utility causes a pinch – known as "utility pinch".

⇒ Case B shows composite curves with two levels of steam. Introduction of second steam level causes utility pinch.

⇒ Same rules must be obeyed around utility pinch as around the process pinch. Heat should not be transferred across it by process-to-process heat transfer, and there should not be no inappropriate use of utilities.

So, these points I have noted which I just discussed case A shows the composite curves, but with two levels of utility instead of one the second cold utility is steam generation introduction of second utility causes a pinch known as utility pinch. Then case B shows composite curves with two levels of steam introduction of the second steam level causes utility pinch. Same rules must be obeyed around utility pinch as around the process pinch the heat should not be transferred across the pinch by process to process heat transfer and there should not be an inappropriate use of utilities.

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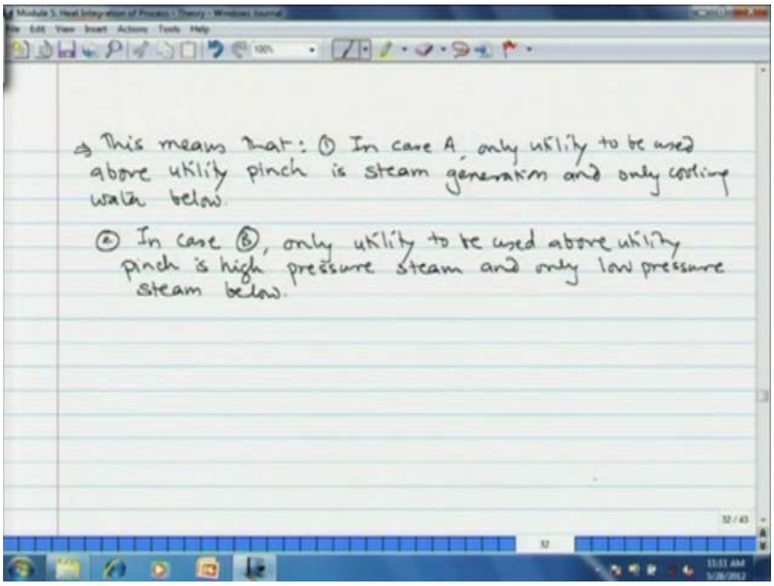

⇒ This means that: ① In case A, only utility to be used above utility pinch is steam generation and only cooling water below.

② In case Ⓑ, only utility to be used above utility pinch is high pressure steam and only low pressure steam below.

This means, that in case a the only utility is to be used above utility pinch is the steam generation and cooling water below in case B, the only utility is to be used only utility is to be used above pinch is the high pressure steam and only low pressure steam. So, that completes the basic discussion on principles of heat integration. In the next lecture, we shall see has how we can determine the minimum hot and cold utility requirement for a particular process using problem table algorithm. Then we shall also see some practical constraints on the amount of heat that is recovered.