Process Integration
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Module - 05
Pinch Design Method for HEN synthesis

Lecture - 02
Rules for Pinch Design Method (PEM) - Part 02

Welcome to the lecture series on process integration. This is module 5 lecture 2. The topic of this lecture is pinch design methods, heuristic rules part two. In the first part we have covered some of the rules and in the second part will come at rest of the rules.

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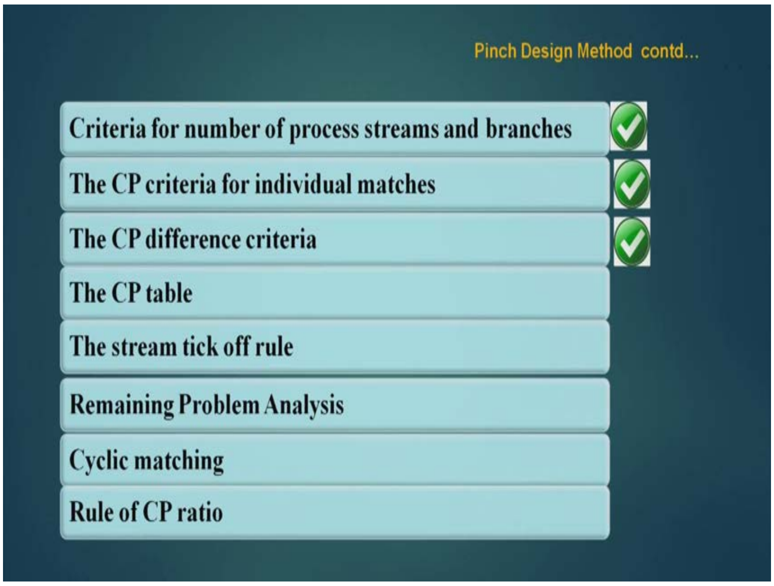

In the first part criteria for number of process streams and branches we have already covered. Then the CP criteria for individual matches we have covered, CP difference criteria we have covered.

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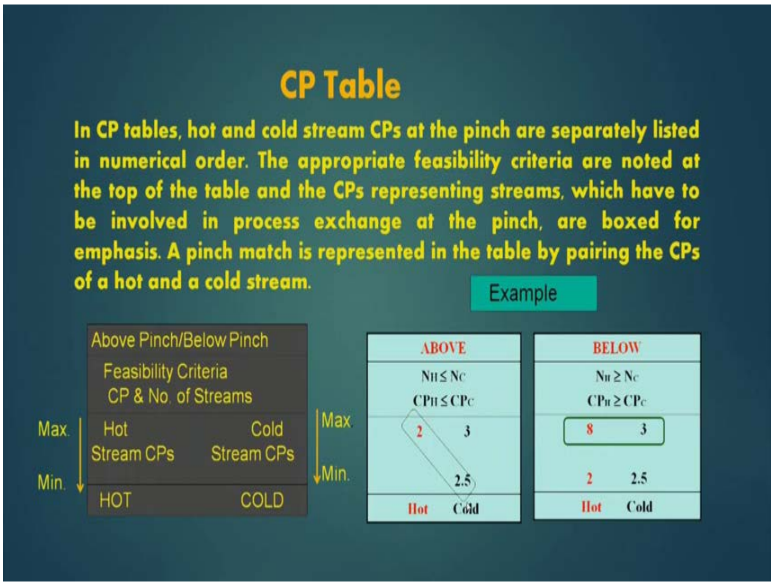

Now, in this lecture the rest will be covered. To start with it will start the CP table, in CP tables hot and cold streams CPs at the pinch are separately listed in numerical order. The appropriate feasibility criteria are noted at the top of the table. The CPs representing streams, which have to be involved in process exchange at the pinch are boxed for emphasis. A pinch match is represented in the table by pairing the CPs of a hot and a cold stream.

Now, first we write down whether it is above pinch or below pinch. Then we write down the feasibility criteria related to CP and number of streams. Then we enter the hot stream CPs and cold stream CPs from maximum to minimum, then we write down here the hot and cold stream. An example will be this table which shows above pinch N H is less than or equal to N C , this is criteria for number of streams. CP H less than or equal to CP C this is criteria for feasibility criteria for CP. Then there is only hot stream which has got a CP value of 2, where is there are two cold streams one has a CP value of 3 other 2.5. So, we are writing from 3 to 2.5 in descending order this is maximum this is minimum.

This shows that this CP is for hot and this shows this CP is for cold.. Now, similarly, for the below pinch reason we write down this is the rule of number of streams N H is should be greater or equal to N C , CP H should be greater or equal to CP C, here there are 2 hot streams having CPs 8 and 2. So, high maximum to minimum we are writing and there are 2 cold streams 3 and 2.5. So, maximum to minimum we are writing. Now, while representing matches we represents matches like this, that is 2 will be matched with 2.5 and here 8 will be matched with 3.

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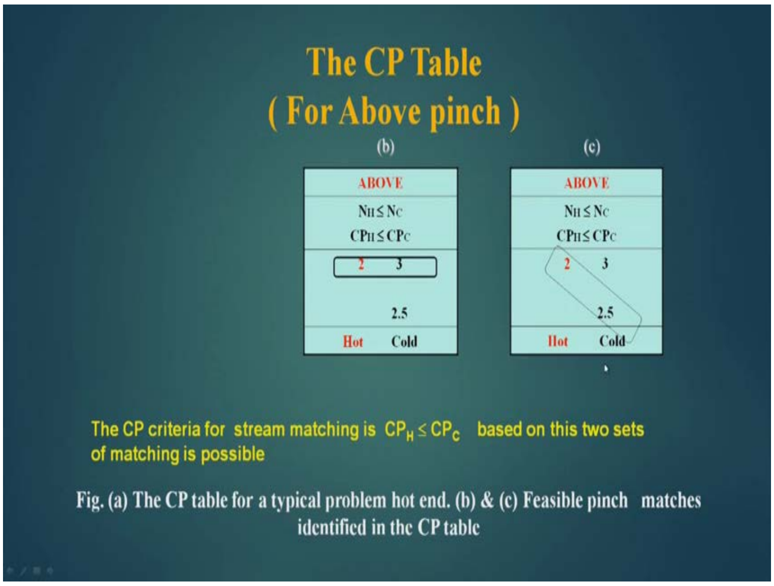

Now, if you see here, this is N C should be greater or equal to N H, here there are two cold streams and one hot stream. So, this number of stream criteria is fulfilled. Now, we have to see that this criteria is fulfilled or not while placing matches. So, I can match this because here CP C which is 3 is more than 2 so this match is permissible or I say this pinch match is permissible. This is also permissible because 2.5 is more than 2 so, this match is permissible. So, I have a freedom to do the matching, I can match 2 with 3 or 2 with 2.5. So, both match is perfectly alright for above the pinch results. Now, if you see the below the pinch results, here N H should be greater or equal to N C.

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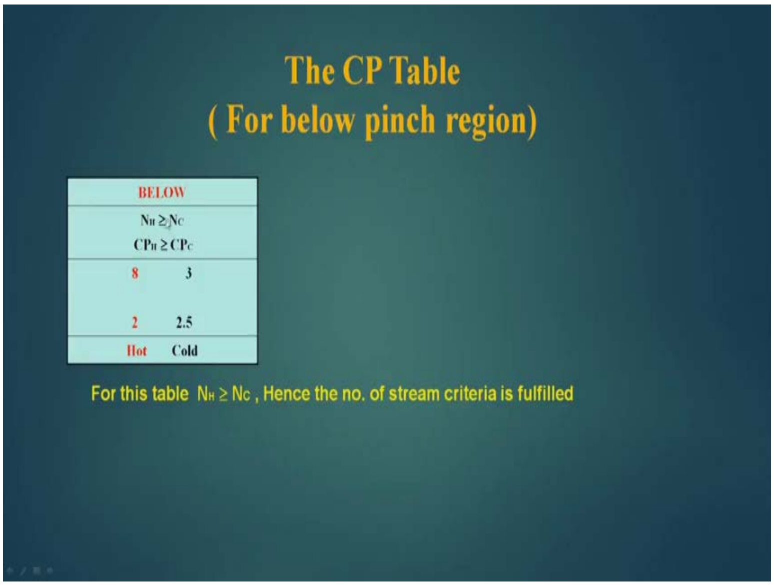

In this condition N H is equal to N C because there are two hot streams and two cold streams so this criteria is fulfilled.

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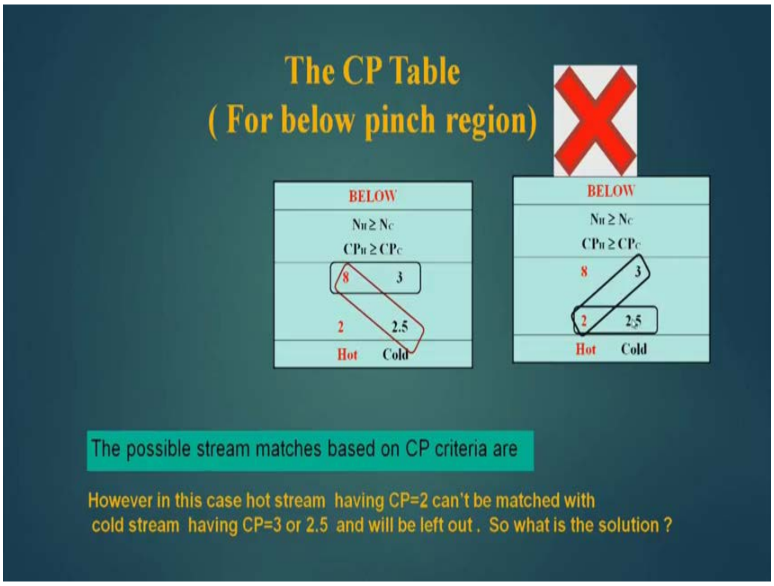

The possible matches are here CP H Should be greater than CP C. So, I can do this matching because 8 is more than 3 or I can go for 8 is more than 2.5. So, I can take this match as well, if I want to do the matching like this 2 to 3 or 2 to 2.5, this is not permissible because this violates this criteria CP H greater or equal to CP C. Here CP H which is 2 is less than 3. So, this is violated here also 2 is less than 2.5 so this condition is violated.

Now, if it is so, it violates a condition here we see that a hot stream has been left out. Here also a hot stream is left out, if I do for go for this matching this is not possible. So, this matching is only possible. So, a hot stream is left out in this matching. Now, if it is left out, then this has to be cooled using utility. If I use utility then the utility may arise and the cost may rise. So, what is the solution for this? Now, we have seen a problem where splitting is the only solution. So, the problem which you face and if you think how to solve it then it comes out that splitting, splitting is the only solution for such cases.

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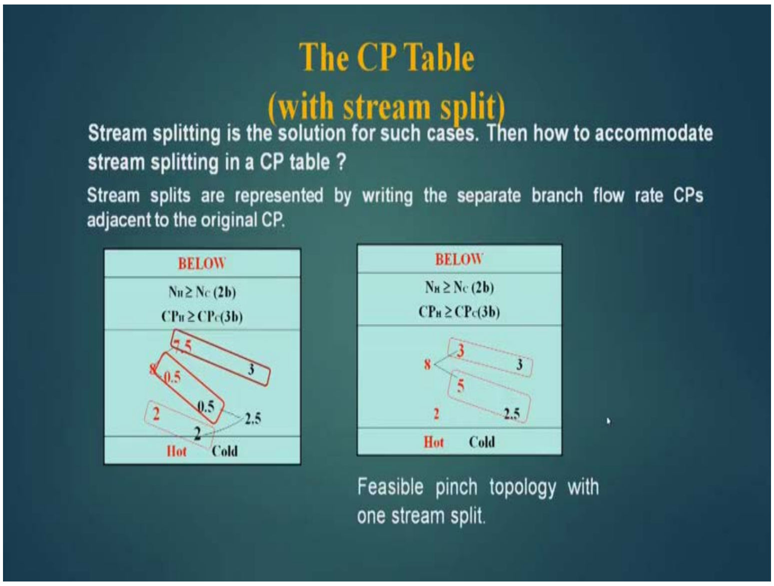

Then the question is how to accommodate the stream splitting in the CP table. Stream splits are represented by writing the separate branch flow rate CPs adjacent to the original CP. Now, if we want to split the stream which has got a CP value of 8 we will write down the adjacent CPs 7.5 and 0.5 here, with a line like this. So, it is all that the 8 is spitted into 2 streams out of which 1 stream has a CP of 7.5 and the other stream has got a CP of 0.5.

Similarly, we can split 2.5 also, into 2 streams one as a CP of 0.5 and the other as a CP of 2. Now, why we have done this splitting business, because by splitting we can satisfy this rule. Now, you can put up matches 7.5 can be matched with 3 because here CP H which is 7.5 is more than CP C which 3.5 with 7.5 because CP H is equal to CP C here, here 2 and 2 can be matched. So, CP H is equal to CP c. So, this is a valid matching.

So, it is a feasible pinch topology with two stream splits because both the rules that is N H should be greater or equal to N C and CP H should be greater or equal to CP C has been fulfilled. Now, I have kind of the second case, where I can break the hot stream which is equal to CP of 8 into two parts 3 and 5 and I can do the matching. So, feasible pinch topology with one stream split

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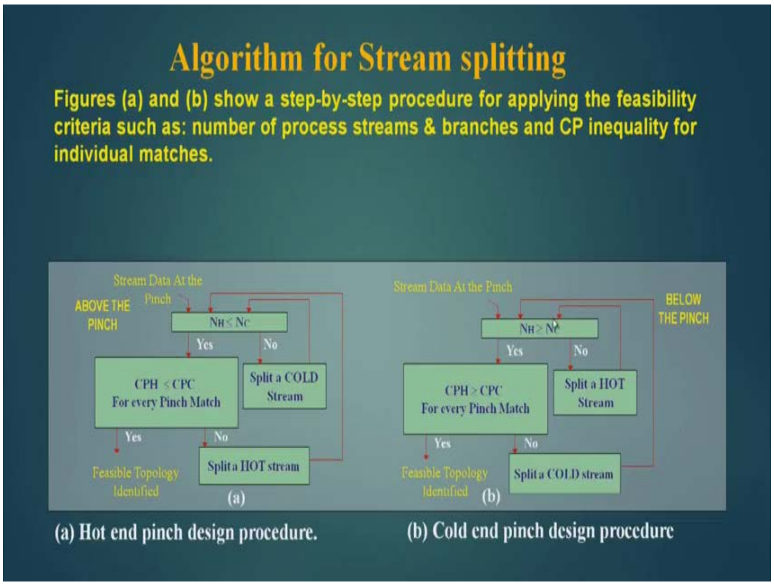

Now, let us see the algorithm of stream splitting. Now, there are two basic rules, which controls the stream splitting that is number of branch rule and that is the other is CP inequality rule. So, if I see the above the pinch area, then first we will check that whether N H is less than N C or not. If it is no then will split a cold stream and again will go to check this rule whether it satisfies or not. If it satisfies then we come back to this line and then check whether CP H is less than CP C or not for every pinch match. If it is yes then the feasible topology is identified or a match is placed. If it is no then split a hot stream and again move to this place.

This is repeated till all the rules are satisfied that is this two rules N H should be less than or equal to N C and CP H should be less than or equal to CP C both are satisfied. Now, for the below pinch this rules reverse here N H is greater or equal to N C and CP H is greater or equal to CP C. So, first test is N H is greater or equal to N C if no then we will split a hot stream and then will move here, if yes will check the CP rule criteria. If the CP criteria is satisfied will place a match and will get a feasible topology identified, if no then we will split a cold stream and again will move to this.

So, here we see that this algorithm takes into account both the rules that is stream of branches rule and CP inequality rule. For conditions above the pinch and below the pinch these rules reverse. So, our basic is that identify essential matches at the pinch, identify available match options at the pinch, identify the need to split streams and generate stream splitting options at the pinch. Now, let us see some problems with stream splitting or its advantage and disadvantages.

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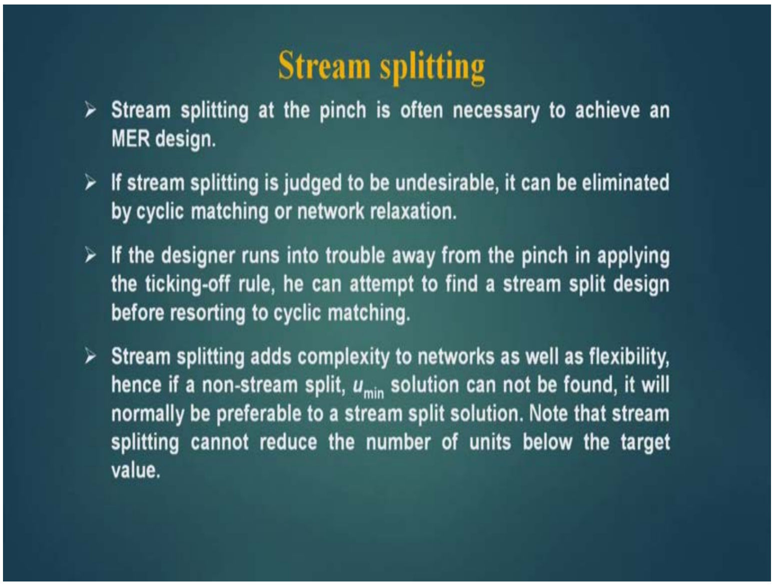

Stream splitting at the pinch is often necessary to achieve an MER design. MER means maximum energy recovery design, if stream splitting is judged to be undesirable, it can be eliminated by cyclic matching or network relaxation. This can be done will see in detail what the cyclic matching does and how this stream splitting can be avoided by cyclic matching, but it has got its own problem. If the designer runs into trouble away from pinch in applying the ticking off rule, he can attempt to find a stream split design before resorting to cycling matching.

This can also be done because we will see it, the tick off rule sometimes loads the problem and stream splitting can be done or cyclic matching can be done to solve this problem. Stream splitting adds complexity to networks as well as flexibility, hence if a non-stream split u minimum solution cannot be found. It will normally be preferable to a stream split solution, note that stream splitting cannot reduce number of units below the target value. Now, we have completed the stream table, we have started a second rule.

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Here, we see a take a problem where there are two hot streams and two cold streams, these are the CP values and this is the table CP table.

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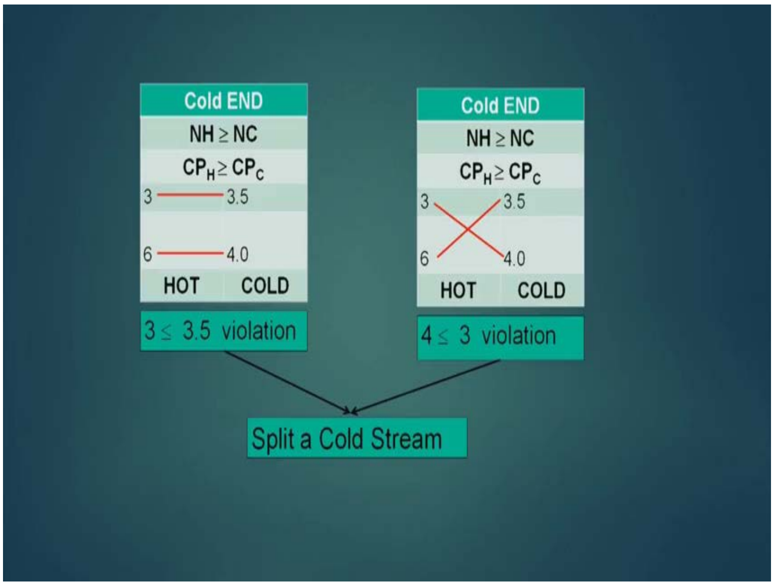

Now, if I try to connect 3 with 3.5 and 6 with 4, then I am doing a violation because in this case CP H is not greater than CP C so this is the violation. Now, if I matching like this then there is another violation. Here CP H is not more than CP C. So, there are 2 violations. Now, if the violation takes place to exist then I have to split a cold stream.

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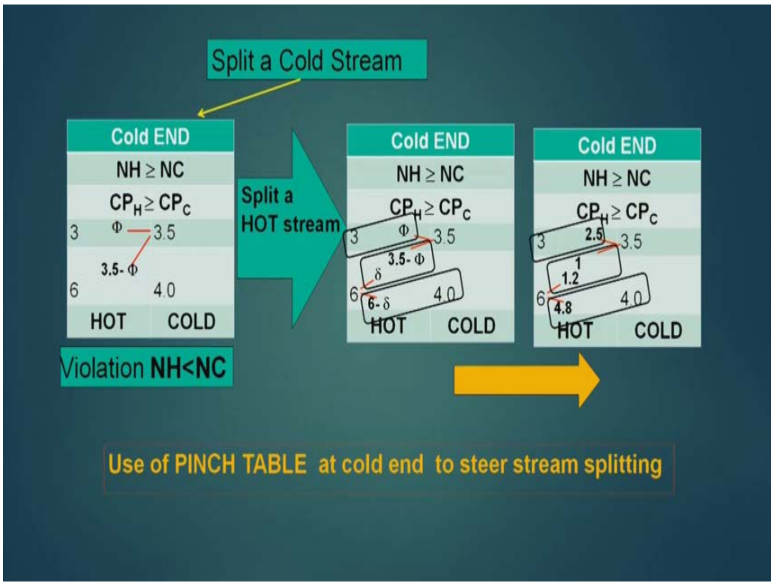

So, what I will do, I will split a cold stream that is I am splitting 3.5 into 2 parts one has a CP of phi and another as 3.5 minus phi. Now, if I do this that is a violation of number of streams or number of split streams at pinch. So, here the correct three cold streams and two hot streams. It says that number of hot streams should be more than number of cold streams or at least should be equal to the cold stream so this is violated. So, to remove this violation I have to split a hot stream. So, I am splitting a hot stream here this hot stream which has got a CP value of 6 is spitted into delta and 6 minus delta. Then I can do this matching, by properly adjusting the value of phi and delta.

Now, let us see when I adjust the value of phi and delta I can have several set of values of phi and delta which will satisfy this conditions, CP H should be greater than or equal to CP C. So, once it is this I will break 3.5 to 2.5 and 1 and 6 to 1.2 and 4.8 and I do this matching. Now, this old end the CP table has been used in the old end of the design to steer the stream splitting. Now, let us see a second rule which is called the tick off heuristic.

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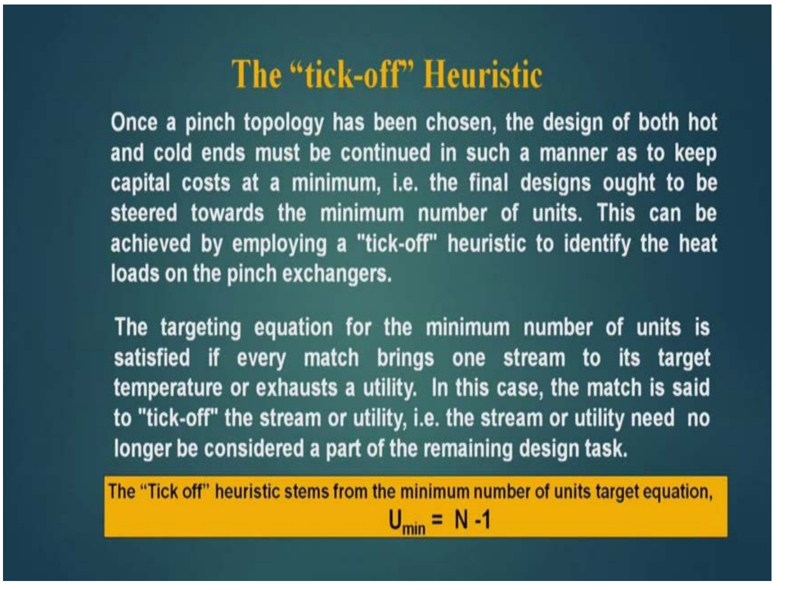

Once a pinch topology has been chosen, the design of both hot and cold ends must be continued in such a manner as to keep capital costs at a minimum. We have already told that when we are designing a heat exchanger network, then the designs will take place in such a way that the cost is minimum, the final design ought to be steered towards the minimum number of units.

So, it is assumed that if the number of units are minimum in a design end design then its cost will be minimum. So, the first attempt will be to decrease the number of units in a end design. This can be achieved by employing a tick off heuristic to identify the heat loads on the pinch exchangers. Here the pinch has given pinch analysis has given a tick off heuristic and this tick off heuristics tends from the minimum number of units target equations.

That means while doing targeting we will see that the at one go the maximum heat of a stream should be transferred to the other stream. The targeting equation for the minimum number of units is satisfied if every match brings one stream to its target temperature or exhausts a utility, the same thing it tells that when we are exchanging it we will try to maximize this exchange. So, that a stream is ticked off, in this case the match is said to be ticked off, the stream or utility. The stream or utility need no longer to be considered as the part of the remaining design task.

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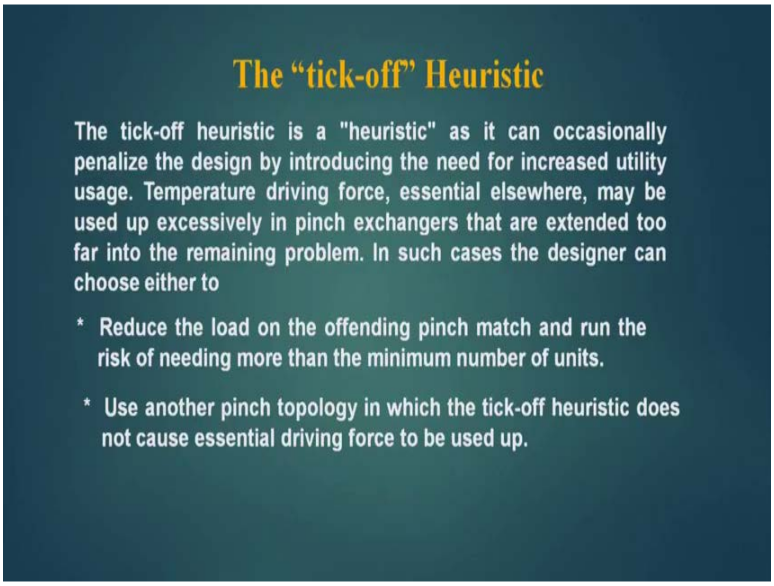

The tick off heuristic is a heuristic, as it can occasionally penalize the design by introducing the need of increased utility usage. This has also been seen temperature driving force essential elsewhere may be used up excessively in pinch exchangers, that are extended too far into the remaining problem. In such case the designer can choose to either reduce the load on the offending pinch match and run the risk of needing more than the minimum number of units or use another pinch topology, in which the tick off heuristics does not cause essential driving force to be used up. Let us take an example to show you the tick up heuristics.

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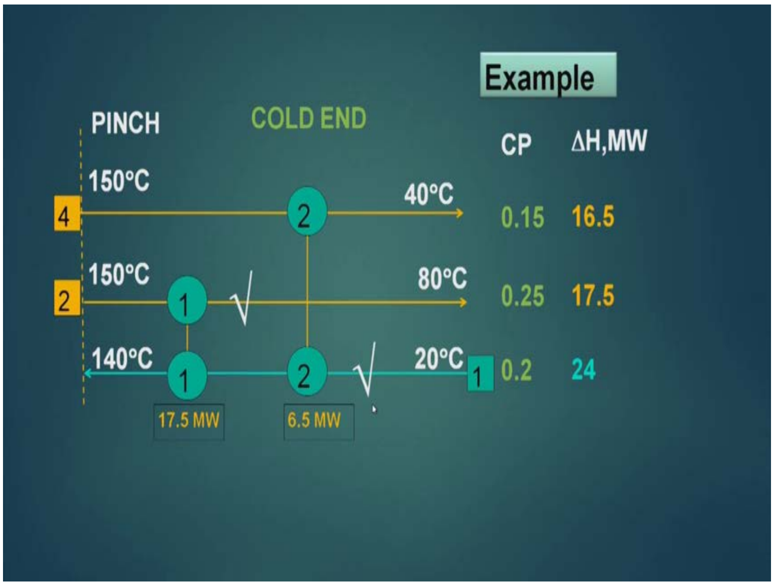

For this purpose we have taken the cold end part of the design. Here we have two hot streams which are moving from pinch temperature which is 150 degree centigrade to 40 degree centigrade, the second stream is moving from 150 degree centigrade to 80 degree centigrade. There is cold stream which starts at 20 degree centigrade and moves to 140 degree centigrade. Now, the CP values are 0.15 for stream number 2 this is 0.25 and stream number 1 is 0.25. The heat available with these 2 hot streams are 16.5 and 17.5.

The heat can be received by this cold stream is 24 megawatt, to hit it from 20 degree centigrade to 140 degree centigrade. Now, based on the CP rules we can place matches. Now, if I place a match 1 1, that is heat exchanger number 1 and if I make it duty as 17.5 megawatt. So, the heat which is available with this stream which is 17.5 megawatt can be directly given to this stream. So, this stream is ticked up that means this stream does not have any residual heat available to give to the cold stream. However, the cold stream has a capability to take more heat because it can take heat up to 24 megawatt.

Now, if I am doing this matching in 2 or 3 heat exchangers then obviously what will happen, the number of heat exchangers will increase. So, when I am doing ticked up that means passing all the heat at one go I am reducing the number of heat exchangers or number of matches. Doing this we are basically controlling the number of units. Now let us say another part of it I can place a second heat exchanger between this stream and this stream. This stream is after taking 7.5 megawatt, this stream is able to take another 6.5 megawatt to hit it from 20 degree to 140 degree centigrade.

So, if I pass 6.5 megawatt from this stream to this stream, then this stream that is number one cold stream will be ticked off. Now, this is how the ticked off heuristics is applied in the design. Now, let us see the third rule which is called remaining problem analysis. Basically it is not a rule, it is a method to steer the design in proper direction.

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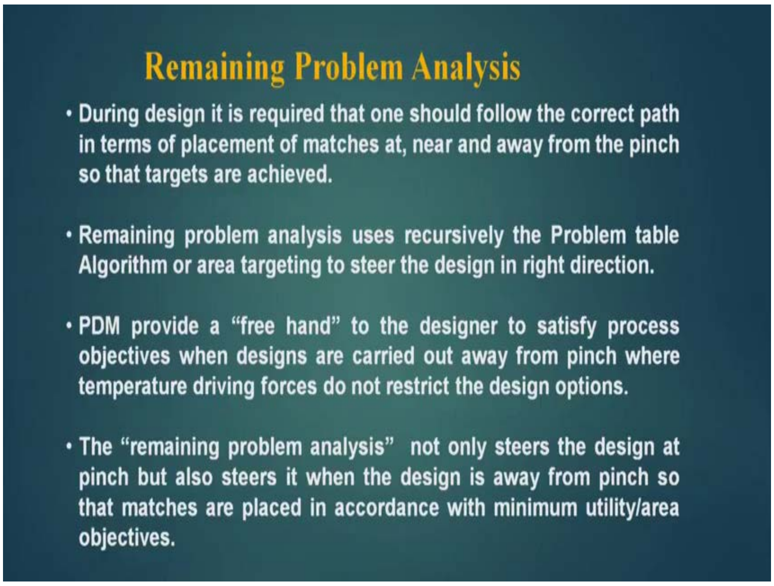

During design it is required that one should follow the correct path in terms of placement of matches, at near and away from the pinch. So, that targets are achieved. We have seen that to place the matches that are be in large numbers alternatives are available. In splitting also, we can split this streams in different way and we can put different matches. The question is whether all the matches are correct or not when I say correct that means all the matches are possible matches will lead to the targeted value or not. Target value in terms of energy or target value in terms of area.

Remaining problem, analysis uses recursively the problem table algorithm or area targeting to steer the design in right direction. That means if I use the problem table analysis then, there is a large chance that I meet the targeted values in terms of energy consumption, hot utility and cold utility consumption or the design. PDM provides the free hand to the designer to satisfy process objectives, when designs are carried out away from the pinch where temperature driving forces do not restrict the design options.

We have already told you that the PDM rules act to be strictly followed for pinch exchangers. If you do not follow it will violate the delta t minimum criteria, but this is not so when we are designing the network away from the pinch, why because away from the pinch the temperature driving force are not restricting one.

There are large temperature driving forces are available as when we go away from the pinch, temperature driving forces increases. The remaining problem analysis not only steers the design at pinch, but also steers it when the design is away from pinch. So, that matches are placed accordance with minimum utility or area objectives. Now, let us see the algorithm for remaining problem analysis. In figure number a, we are using the PDA for this purpose and in b we are using the area for his purpose.

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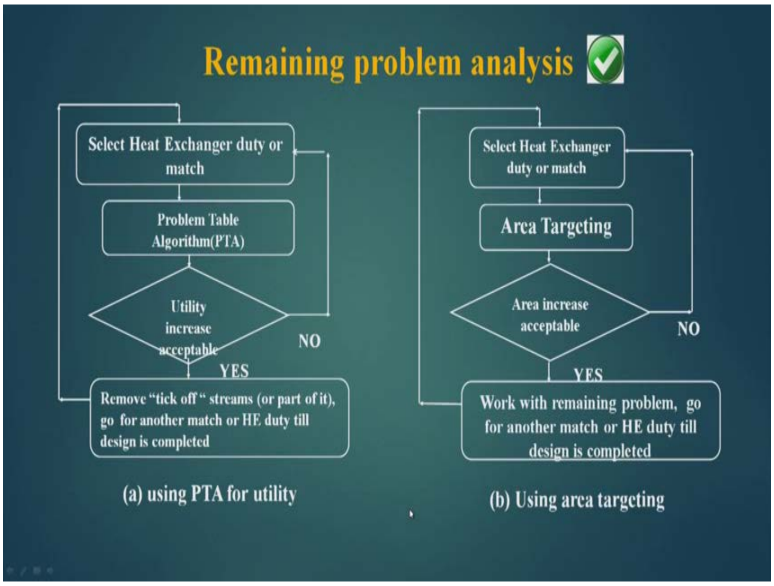

That is the area targeting, in first case we are basically using energy targeting. For energy targeting we are using the problem table algorithm. So, to start with PTA for utility targeting in the remaining problem analysis, when the problem is given to us then, we first to the PTA analysis of the problem and find out what is the hot utility requirement and what is the cold utility requirement. Now, after knowing this we go for the design. So, in the design we can go for the hot end design as well as cold end design.

So, what generally is done that, start with a hot end design select a heat exchanger duty or a match and then do the problem table algorithm the problem table algorithm in the for the rest of the matches. When we do this, we automatically reduce the value of the match and then we apply the problem table algorithm. Now, if the utility increases and if the increasing utility is acceptable, then we should go for remove tick off stream or part of it and go for another match or heat exchanger duty till design is completed.

If it is a match is accepted that is increase in the exchanger of the hen utility is acceptable, then we go for a second match. While doing so we remove the stream or part of it which has been ticked off already and again do the PTA analysis after putting up the second match. Then again see whether there is a increase in the utility level or not.

If the utility level is not accepted then we do not go for that match which is analyzing the utility and we try to search for a alternative match. This way we proceed till we the design is steered in the proper direction. So, that we are not deviating much from the hot utility, total hot utility, total requirement and total cold utility requirement of the problem.

This remaining problem analysis will be very clear when we take this lecture on remaining problem analysis. Now, similarly, the use urea area targeting can also be utilized for remaining problem analysis. In this we select a heat exchanger duty on match, then we do the area targeting. Whether we see the area increase is acceptable or not if yes, then work with the remaining problem go for another match or heat exchanger duty will be design is completed, then we go and put another select match.

If no then we go this way and select another heat exchanger duty or another match and again do the area targeting and see whether total area has increased or not. If not increased, then we can directly go and put a second match, if yes then we have to do the remaining problem analysis and see whether area is increasing or not. Now, the third part is cyclic matching. Now, in some times it is not possible to do splitting and if it is so, then what is the way out. So, we will see that there is a way out, which is called cyclic matching.

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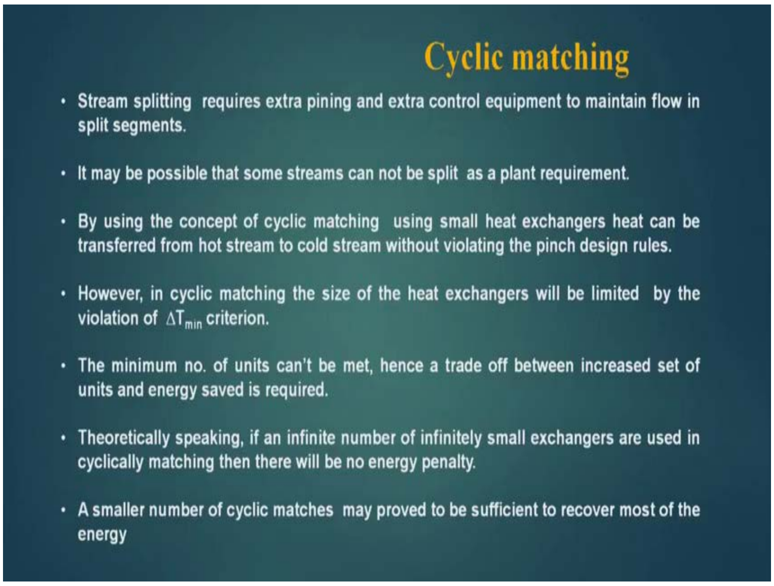

Stream splitting requires extra piping and extra control equipment to maintain flow in split segments. It may be possible that some streams cannot be split as a plant requirement, by using the concept of cyclic matching using small heat exchangers heat can be transferred from hot streams to cold stream without violating the pinch design rules.

However in cyclic matching the size of the heat exchangers will be limited by the violation of delta t minimum criteria, the delta t minimum criteria will control that what could be the capacity of the heat exchanger or what load the heat exchanger take up. The minimum number of units cannot be met in this case. Hence a tradeoff between increased set of units and energy saved is required because if I want to save more energy more number of units has to be used.

So, there is a tradeoff between the these two factors. Theoretically speaking if an infinite number of infinitely small exchangers are used in cyclically matching, then there will be no energy penalty. This means see in numerical code, a smaller number of cyclic matches may proved to be sufficient to recover most of the energy. Now, let us take an example.

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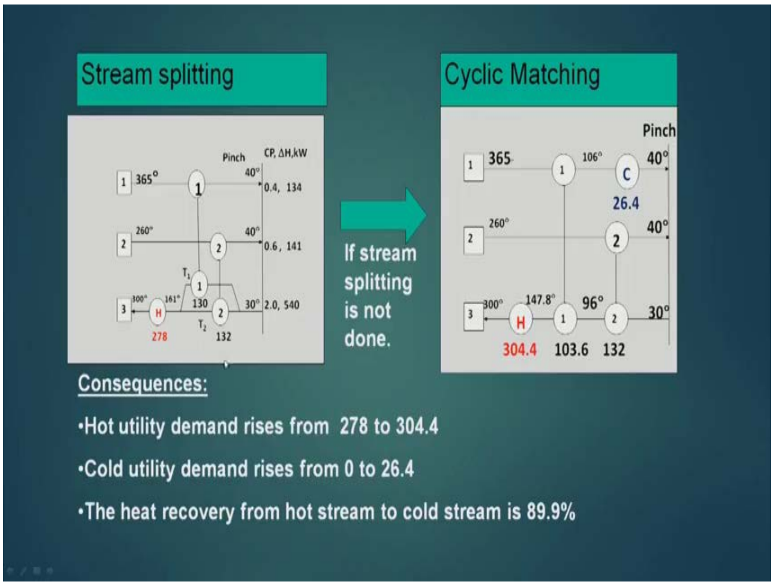

Now, this is a case where we have solved this case by stream splitting. The hot utility requirement is 278 and there is no cold utility requirement. Now, suppose stream splitting is not allowed, then we can go for cyclic matching. Here we see that we have put 2 heat exchangers that is a 2 cyclic matching one heat exchanger number 1 and 2 heat exchanger 2 here. There is a heater and there is a cooler. Now, the distance difference between temperature here the 106 and 96 degree centigrade. So, I am satisfying the delta t minimum from criteria here. Here also delta t minimum criteria is satisfied. So, this load which is 103.6 will be decided by this difference.

Then what should be the load so that the delta t is 10 degree here. Now, if I do the matching like this, then if find that the hot utility requirement has increased for 278 to 304.4 and there is a demand of cold utility requirement 26.4. Whereas, here there is no cold utility demand. So, what are the consequences of cyclic matching, the hot utility demand rises from 278 to 304.4, the cold utility demand rises from 0 to 26.4, the heat recovery from hot stream to cold stream is only 89.9 percent. Now, is it possible to improve this, the answer is yes it is possible. When you will be using more number of cyclic matching then this requirement will move towards this. Here if we count there are 4 heat exchangers required here whereas, 3 heat exchangers are required here.

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So, the number of units are increased during cyclic matching. Now, you take a 3 matches, the same problem is solved by 3 matches, 1 2 and 3, here I have used a cooler and here there is a heater. We see that the hot utility requirement has considerably decreased and cold utility requirement has considerably decreased because we have used 3 matches. Similarly, here I am using 4 matches for that for that there is a decreased in cold utility requirement this is 2.58 only. The hot utility requirement has fall down to 280.58 and the heat recovery is 99 percent.

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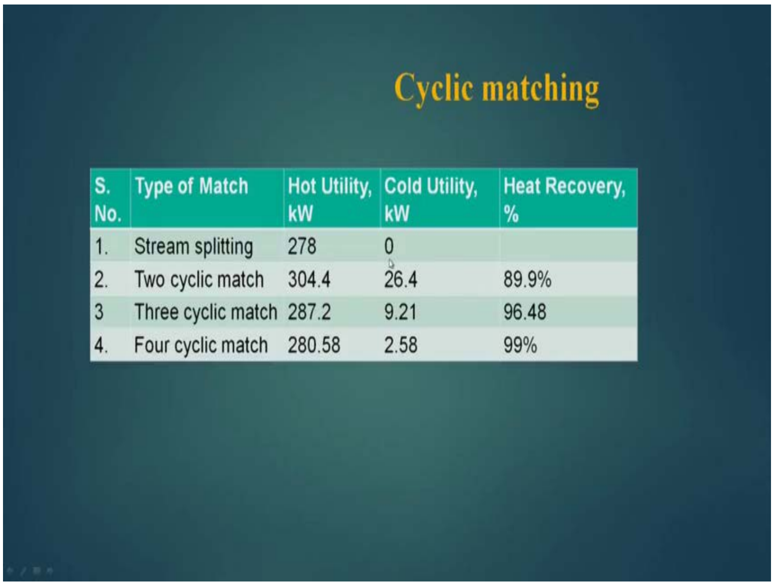

S. No.	Type of Match	Hot Utility, kW	Cold Utility, kW	Heat Recovery, %
1.	Stream splitting	278	0	
2.	Two cyclic match	304.4	26.4	89.9%
3	Three cyclic match	287.2	9.21	96.48
4.	Four cyclic match	280.58	2.58	99%

So, for the cyclic matching this conclusion we draw, if I am using a stream splitting my hot utility requirement is 278 and cold utility is 0, if I am using 2 cyclic match then this is 304.4 and 26.4 89.9 percent heat recovery. When I use 3 cyclic match it has dropped down to 287.2 and this has dropped down to 9.21, when I use 4 cyclic match I get it 280.58 here and 2.5 8 and 99 percent heat recovery. So, when I am increasing the number of match cyclic matches I am moving towards the hot utility requirement and cold utility requirement as given by the stream splitting topology, but number of units are increased.

So, I am saving energy of cost of number of energy its increased number of units. Now, let us see a rule which is call as CP rule for minimum area network. Now, will see that when we designing heat exchanger network, always the heat exchanger network will not give the minimum area as targeted by the area targeting. This rules sets some light on it why we do not get a minimum area network.

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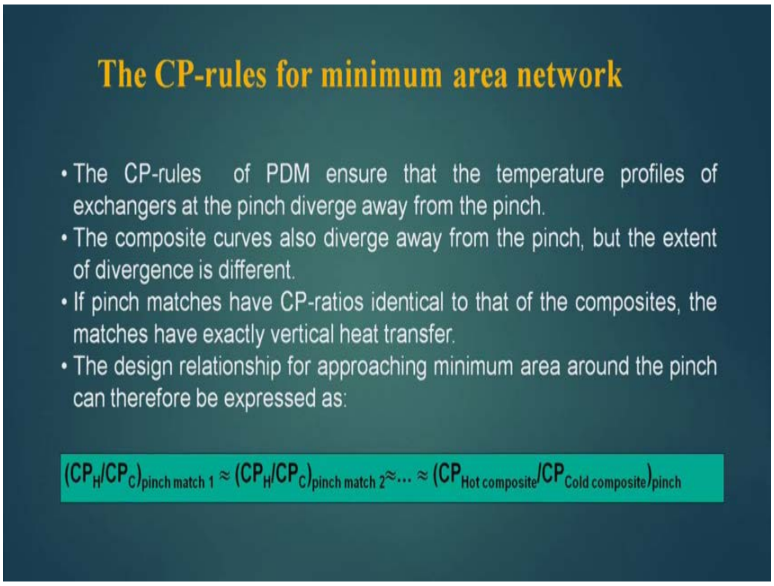

The CP rules of PDM ensures that the temperature profiles of exchangers at the pinch divers away from the pinch. This the rule the CP rule are made for this, the composite curves also diverge away from the pinch, but the extent of divergence is different. That means if I compare the divergence of a heat exchanger, or a pinch heat exchanger with that of the composite curve which is available in that area, we will see that the divergence are different in nature. If pinch matches are CP ratios identical to that of the composites the matches have exactly vertical heat transfer.

It says that if I find out this CP matches for the heat exchangers and I compare it with the composite CP matches and if they near to the composite CP matches, then whatever the area I will get for those heat exchangers will be almost minimum. So, the design relationship for approaching minimum area around the pinch can therefore be expressed as CP H by CP C for match 1 should be equal to CP H by CP C of match 2. So, on for match 3, match 4, match 5, match 6 and they also be equal to almost equal to CP H hot composite by CP cold composite at pinch.

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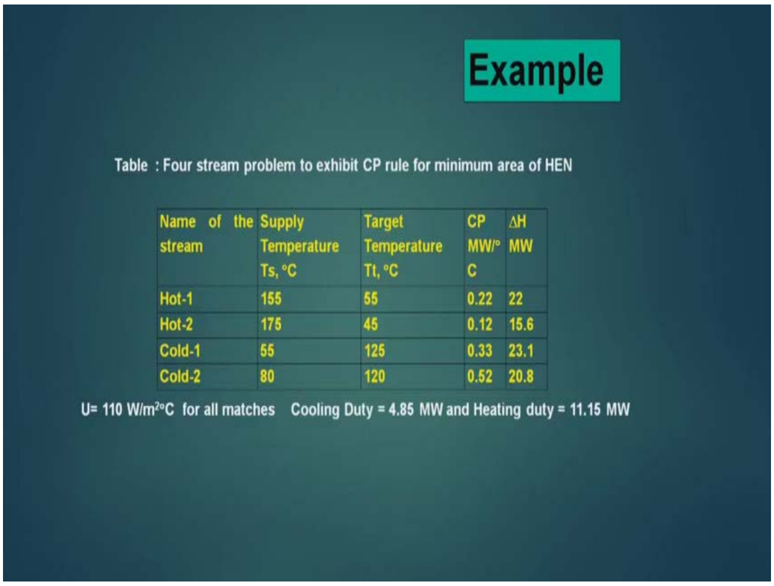

Name of the stream	Supply Temperature Ts, °C	Target Temperature Tt, °C	CP MW/°C	ΔH MW
Hot-1	155	55	0.22	22
Hot-2	175	45	0.12	15.6
Cold-1	55	125	0.33	23.1
Cold-2	80	120	0.52	20.8

Now, we demonstrate this with an example, this is a 4 stream problem taken here u is 110 bar meter square centigrade for all matches cooling duty is 4.85 megawatt and heat duty is 11.15 megawatt.

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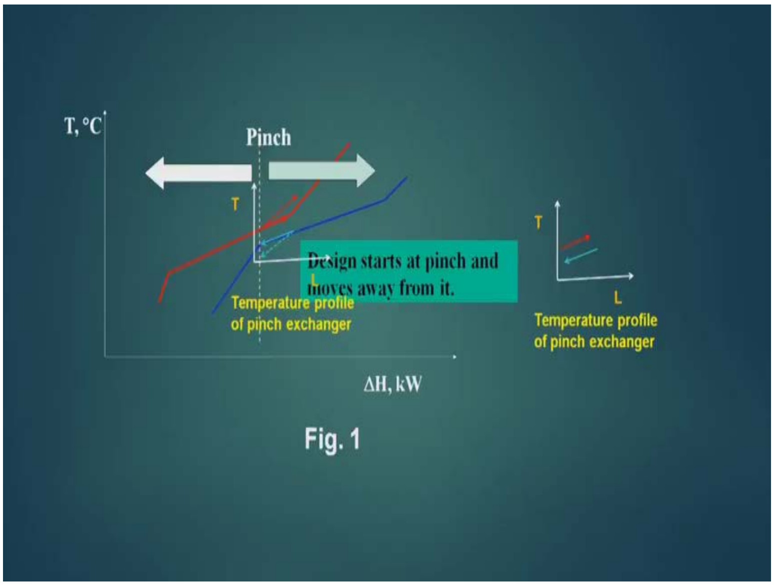

Now, this is the suppose this is the this is a composite curve, here this is expanding that means this distance is minimum. Here it is more here it is more and more. Now, here if I am tracing a heat exchanger here, the temperature profiles of the heat exchangers length is this. If this matches with here then the design will give minimum area. So, it matches here now that can be a case where they are not matching say this is a case where it is not matching.

If it is not matching then it is difficult to guaranty that heat exchanger which will be calculated will give you a minimum area. So, it gives you a rule to place the heat exchangers, that means if CP hot by CP cold the ratio is equal to the ratio at pinch. Then we should place that match, if is deviating much we should not place that match.

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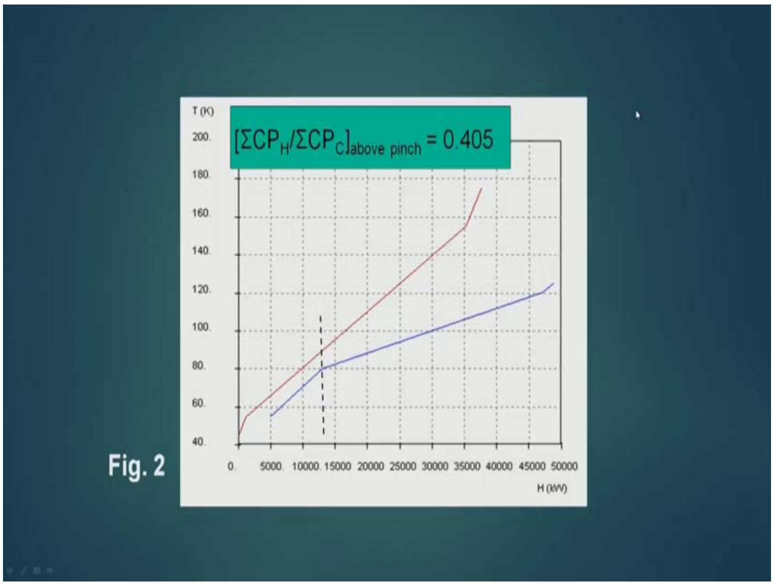

It will be more clear from the next example. Now, we have taken this stream table then we have plotted the composite curve here. Now, here near the pinch the summation of CP H by summation of CP C above pinch area, this is above pinch area it is 0.405.

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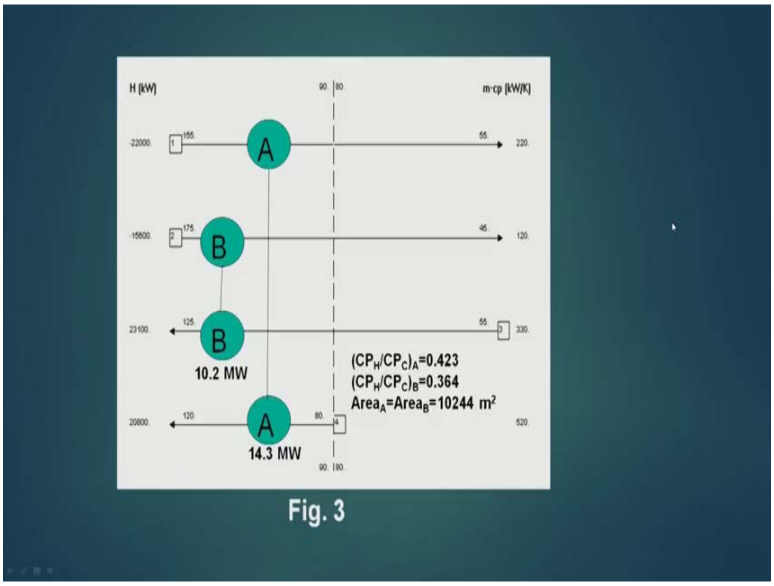

Now, this is above pinch area if I place my heat exchanger B, between this stream number 2 and stream number 3 and the load is 102 megawatt. Then for B the ratio is 0.364 and for a the ratio is 0.423 and the area of a plus area of B is 10244.

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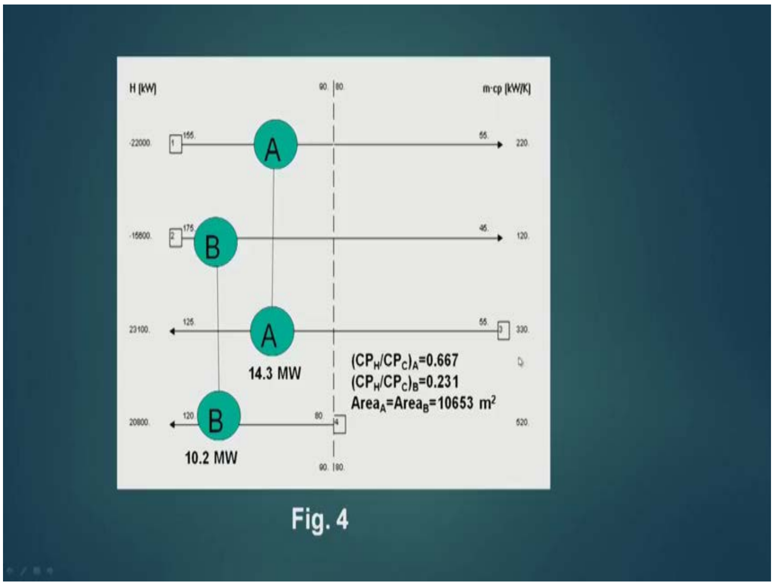

Now, in this case I am keeping this same node for heat exchangers, but it is placed between different other streams. So, here CP H by CP C of a is 0.667, here CP H by CP C of B is 0.231 then area a plus area B is 10653. So, here the area is more because this ratios are not close to the ratio of which is for best up 0.405. Now, if I see the first case here. The ratios are somewhat near to that value, composite CP ratio values and that is why area A plus area B is equal to 10244, but when they deviate much when this ratio deviate much and this case then the area a plus area b is 106353 which is far more. So, placement of match like this is not correct.

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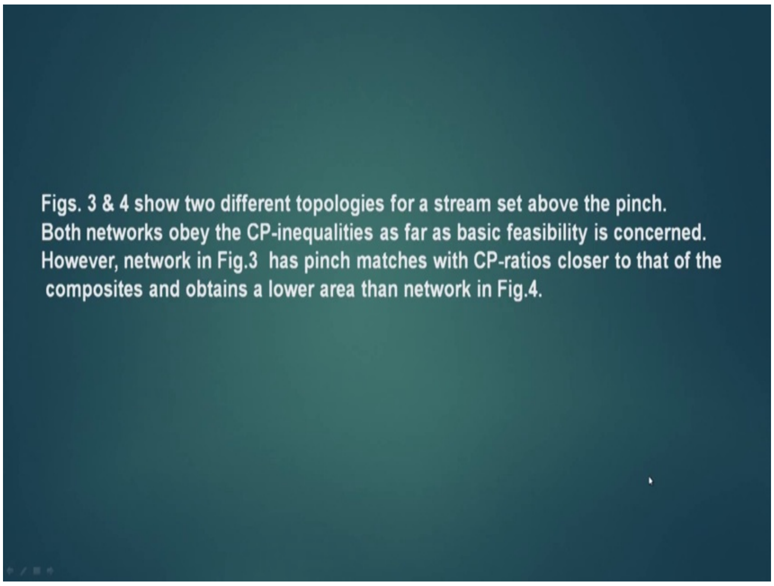

So, this rule also tells me that how to put the different matches based on CP ratios. So, concluding figure 3 and 4 shows different topologies, for a stream set above the pinch. Both networks obey the CP inequalities as far as basic feasibility is concerned. However network in figure 3 has pinch matches with CP ratios closer to that of the composites and obtains a lower area than network 4. So, our CP rule is over.

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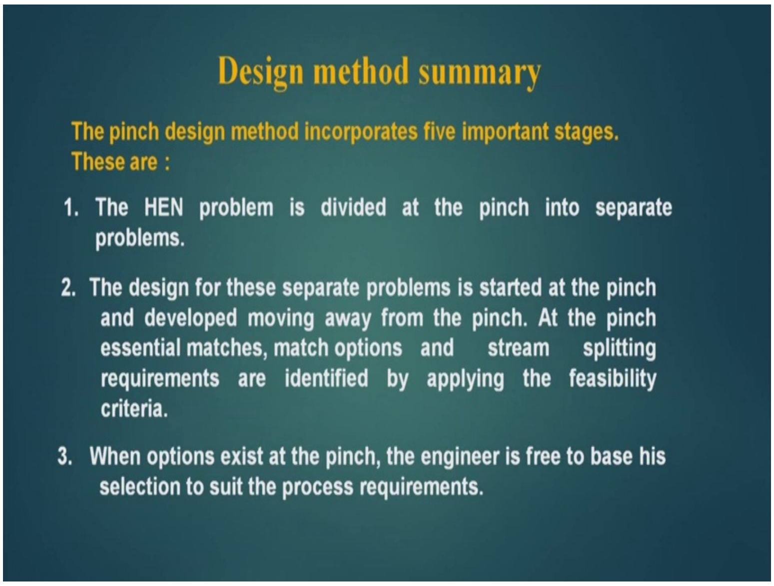

So, let us have the summary of the design methodology. The pinch design method incorporates 5 important stages these are, the hen problem is divided at the pinch into separate problems. So, the total hen problem is divided into the pinch by upper half reason, lower half, upper half is hot end and lower half is cold end. So, the pinch design methodology divides the hen problem into two distinct or separate problems, which are thermally in equilibrium or thermally sufficient.

The design for this separate problem is started at the pinch and developed moving away from the pinch, why this is taken we have already explained. At the pinch essential matches match options an stream splitting requirements are identified by applying the feasibility criteria. When options exist at the pinch the engineer is free to base his selection to suit the process requirements. We have seen that there are many of options exist at the pinch. So, the engineer is free to choose, but you select in such a way that area targeting or the hot utility cold utility targeting do not increase much.

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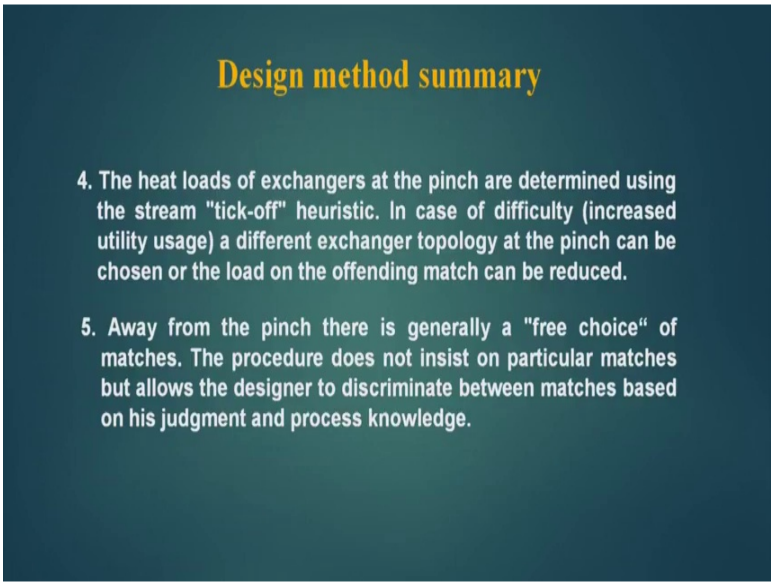

Fourth, the heat loads of exchangers at the pinch are determined using the stream tick off heuristic. This is necessary to control the number of heat exchangers into the hen because if the number of heat exchangers will increase, the cost of the hen will increase. In case of difficulty increased utility usage, a different heat exchanger topology at the pinch can be chosen or the load on the offending match can be reduced. Away from the pinch there is generally a free choice, this is very important because if we are designing non pinch heat exchangers then there is a free choice available.

The procedure does not insist on particular matches, but allow the designer to discriminate between matches based on his judgment and process knowledge. Here we have to see that in low case we should not violate the delta t minimum, but the CP criteria can be diluted to some extent. Thank you.