# Process Integration

**Prof. Bikash Mohanty**
**Department of Chemical Engineering**
**Indian Institute of Technology, Roorkee**

## Module - 5
## Pinch Design Method for HEN Synthesis
## Lecture - 7
## HEN Optimization

Welcome to the lecture series on Process Integration. This is module-five, lecture number seven. The topic of this lecture is HEN optimization - that is heat exchanger network optimization, loops and paths. I have already told you that there exist a trade-off between number of units and the consumption of hot and cold utilities. In the last lecture, we have seen that more is the number of pinch points more will be the number of heat exchangers which will be used in the HEN, because no more will be the duplication. That is why when we go for MER design, we always get more number of heat exchangers, because the streams are counted more times. In the last problem, we have seen that the number of heat exchanger requires were 12 and when we consider a non-MER design; that means, we pass heat from the pinch, the number of heat exchanger drop down to 7. So, there was a scope of saving 5 heat exchangers by converting the MER design to a non-MER design.

Now what is the difference between MER and non-MER design. In a MER design, we guarantee minimum hot utility and cold utility; whereas in a non-MER design, we cannot guarantee it. So, in variably in non-MER design, the amount of hot utility and cold utility will increase. Though we are able to decrease the number units in non-MER design, the hot utility and cold utility requirement increase, thereby it increase the operating cost of the heat exchanger network. Whereas the non-MER design will decrease the fixed cost of the heat exchanger network by decreasing the number of unit. So, there is the trade-off between these two decrease in the heat exchanger network cost that is fix cost and increase in the operating cost.

So, if there is a profit that means, if the TAC - total annual cost, decreases by converting the MER design to a non-MER design, we will go for it; and if it does not decrease, then we will not go for it. So, the conversion of a MER to non-MER design is subjected to the profit, which we get by decreasing the TAC of the HEN.

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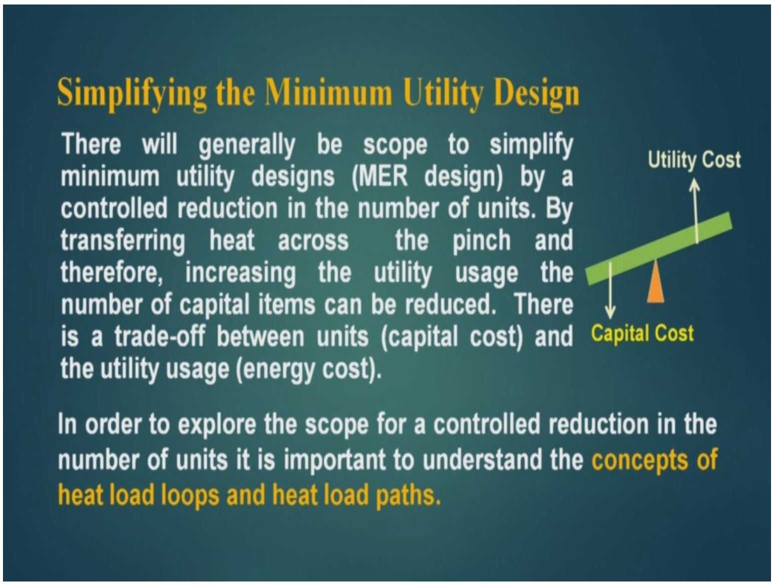


Now let us see there will generally be scope to simplify minimum utility designs that is MER designs by a controlled reduction in the number of units. By transferring heat across the pinch and therefore, increasing the utility usage the number of capital items can be reduced. There is a trade-off between the unit capital cost and the utility usage energy cost; here if you are decreasing the capital cost, the utility cost increases. So, how to balance this is main job.

Now let us see it detail. In order to explore the scope of a controlled reduction in number of units, it is important to understand the concept of heat load loops and heat load paths. We have seen in the units target, if a loop is present in the heat exchanger network, it will increase the number of unit by one; to a single loop will increase the number of heat exchanger by one. Two loops by two number, three loops by three numbers and so on and so forth. In the last lecture, you have seen that the heat exchanger network contain 12 heat exchanger for a MER design rather a two pinch, one utility pinch one process pinch. If I go for a non-MER design, it will drop down to the 7 number of heat exchanger; that means, in that design - MER design 5 loops are present, because it is reporting 5 more number of heat exchanger in the comparison to the MER, non-MER design when I consider a heat flow from the pinch.

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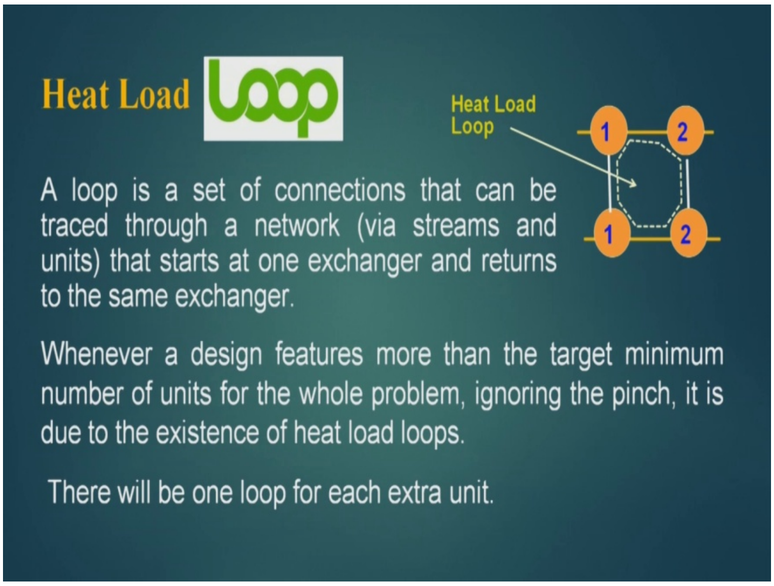


Now let us see the concept of the heat load loops and heat load path. Heat load loops - a loop is a set of connection that can be traced through a network via streams and unit that start at one exchanger and returns to the same exchanger. Now if I start from here, I can go to t two then I can via this, I can go to for again one, then I can go to same place, come to the same place. So, this is the heat load loop. And we will see that such loop are present in MER design, and breaking such loops will be able to decrease the number of heat exchangers. Whenever a design features more than the target minimum number of unit for the whole problem, ignoring the pinch, it is due to the existence of the heat load loops. There will be one loop for each extra unit. And we have clearly understood this.

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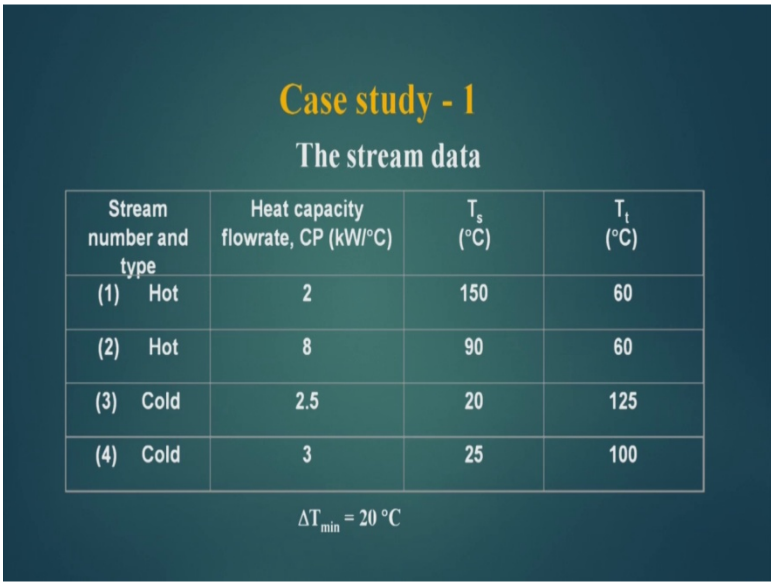
Case study - 1

The stream data

| Stream number and type | Heat capacity flowrate, CP (kW/°C) | $T_s$ (°C) | $T_t$ (°C) |
|---|---|---|---|
| (1) Hot | 2 | 150 | 60 |
| (2) Hot | 8 | 90 | 60 |
| (3) Cold | 2.5 | 20 | 125 |
| (4) Cold | 3 | 25 | 100 |

$\Delta T_{min} = 20$ °C

Now let us take a case study. We have taken the stream data of this table delta T minimum is 20 degree centigrade.

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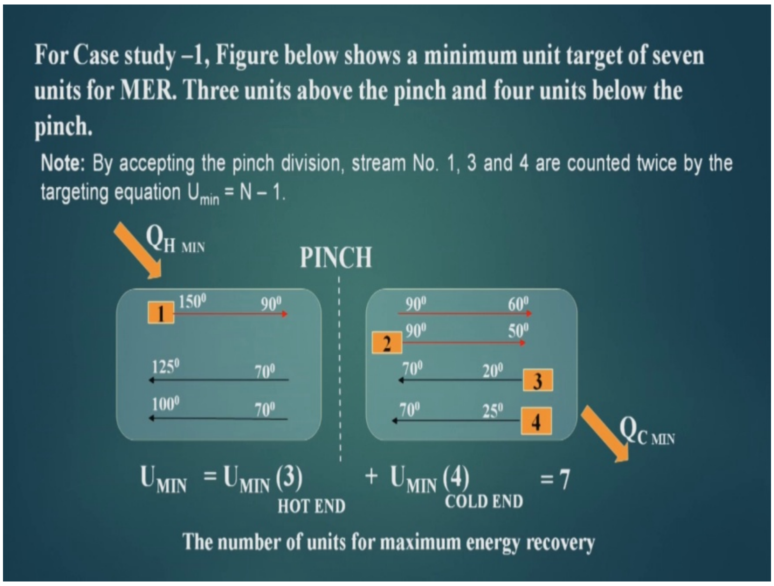


Now for the case study one figure below shows a minimum target of seven units of MER. Three unit above pinch and four unit below the pinch. Now if I apply the units target here, so there are four; that means, three process stream and one utility stream that makes it 4 minus 1, so there are three number of heat exchangers will be placed here including the heater. If I put the target units target here, so there are four process stream one utility stream that makes it 5 minus 1 - four number. So, 3 plus 4 is equal to 7. And here there is no heat is passing through the pinch and hence this is MER design - maximum energy recovery design. Now why this has happened? By accepting the pinch division, stream number 1, 3, 4 are counted twice by the target equation U minimum N minus 1, and due to this twice counting of this stream numbers, the number of units in this MER design has increased.

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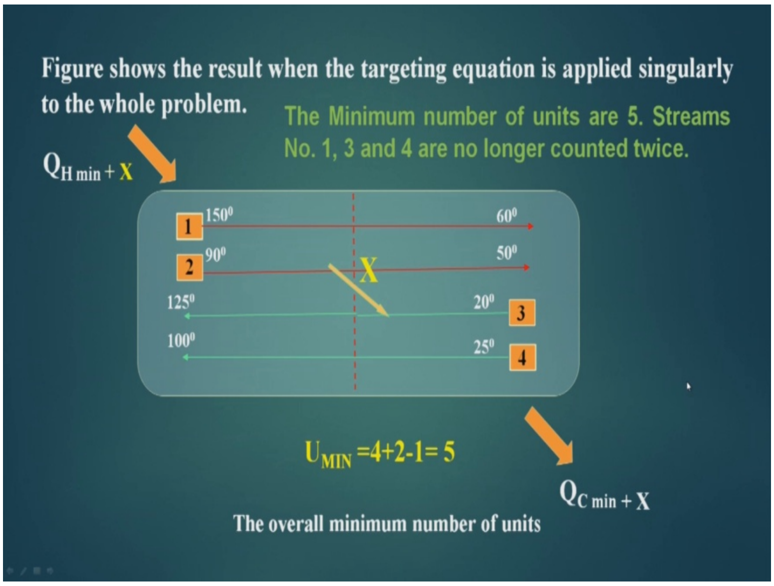


Figure shows the result when the targeting equation is applied singularly to the whole problem. Are this will become whole problem, when we allow heat to pass through the pinch. In general, in MER design heat is not passed to the pinch and that is why the design is divided into two part, which are not thermally connected. But if we pass heat from the pinch, this will be a singular problem, and here the streams will not be counted twice. If I apply here the units target, there are four process stream and two utility stream that makes it 6, and U minimum is 6 minus 1 equal to 5. So, number of minimum number of unit will be 5 in this case; that means, two units can be decreased if I allow to pass this heat of X amount through the pinch.

So, my gain will be two unit, but what I lose the Q H minimum increases by X amount and the Q C minimum also increase by X amount. The first loss, which I encountered is increase in the utility cost by increasing the amount of utility. The second thing is that to pass this X amount of heat and to receive this x amount of heat in cold utility, we have to provide area. So, that much of area will increase in the heater and cooler. So, there is a penalty, which has to be paid if we pass heat through the pinch and then the design is no more MER. So, if I pass it through the pinch, I will call it a non-MER design.

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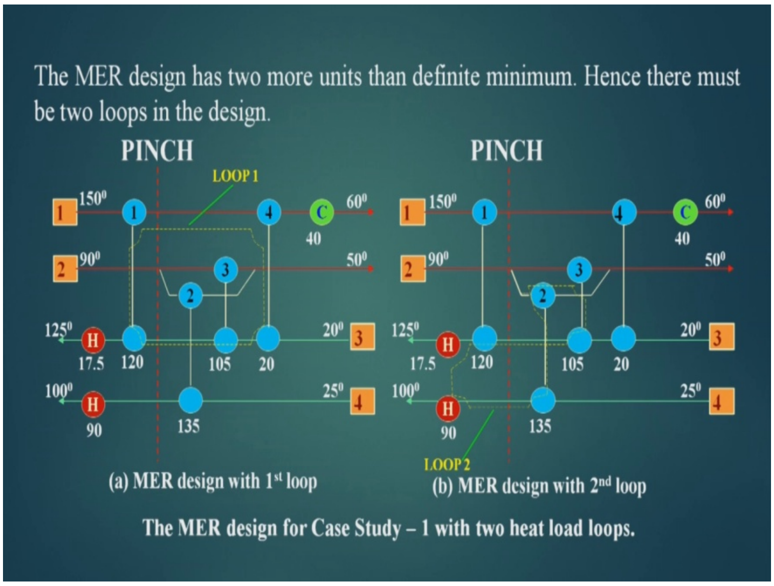


The MER design has two more than the definite number of five. Hence there must be two loop in the design. So, if I see this HEN design then I should find out two loops here, this is the pinch division, the first loop is this. I can start from here, I can go here, I can go up to here, and then here and then come back, so this is the loop. So, my first loop is this. As calculated because two more heat exchanger I am putting up in a MER design, so there must be two loops here. So, one loop I have identified here.

The second loop will be here. So, if I start from here, if I change something here, it is automatically changed, because this and this the value of the size of this in terms of delta H, and this is constant and equal to the total hot utility requirement and that is why if I change this value here, it will be automatically changed. So, there is a connection between these two. So, it goes here, then goes here, then goes here, then goes here, and then goes here and then comes here and then goes here. So, there is a second loop here. Now our aim is to break this loops to decrease the number of unit. Now what should be the scientific way of loop breaking, so that the penalty should be minimum, and this is what we have to search.

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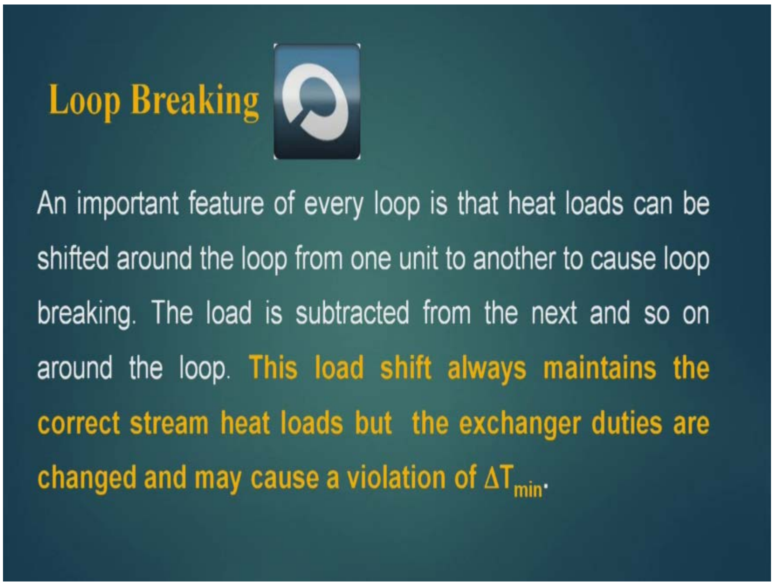


An important feature of every loop is that heat loads can be shifted around the loop from one unit to another to cause loop breaking. If there are two heat exchanger in the loop, I can eliminate one exchanger by adding the capacity of that heat exchanger to the other heat exchanger, which is the loop. This can be done, this is the property of a loop. The load is subtracted from the next and so on around the loop. So, what is being done an important feature of this loop, every loop is that heat load can be shifted around the loop from one unit to another to cause loop breaking. The load is subtracted from the net and so on around the loop.

This load shifts always maintains the correct stream heat loads, but the exchanger duties heat changed and may cause a violation of delta T minimum. Though the exchanger loads are balanced during this; that means, the targeted temperatures will be achieved. But one thing we will see while doing that is, it may violate or in most of the cases, it violate the delta T minimum criteria. Because we are passing the heat through the pinch and that is why it will violate the pinch criteria, we are violating the pinch criteria that is why the delta T minimum will be violated.

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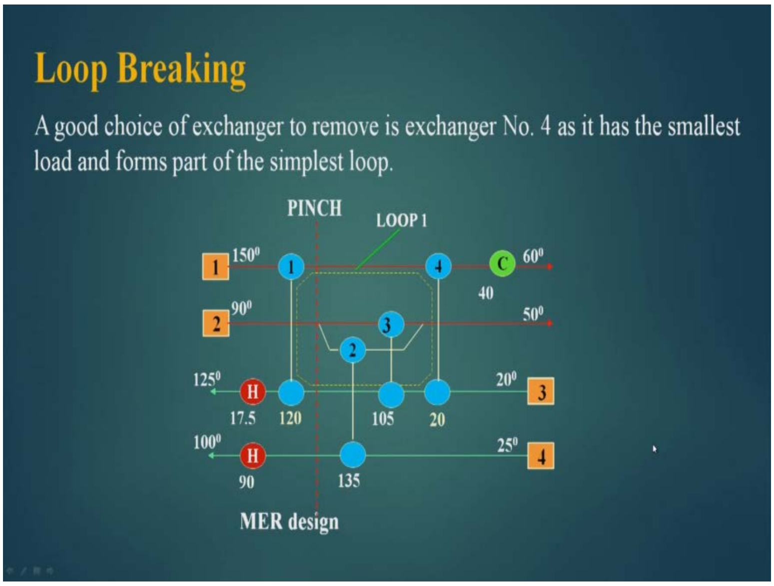


So, we take the first part of it. Now suppose we want to break the loop, a good choice of the heat exchanger to remove the heat exchanger 4 as it has the smallest load and forms the part of the simplest loop. Now if you see this, this heat exchanger number 4 has got the smallest capacity 20, and hence this is the ideal heat exchanger to be removed.

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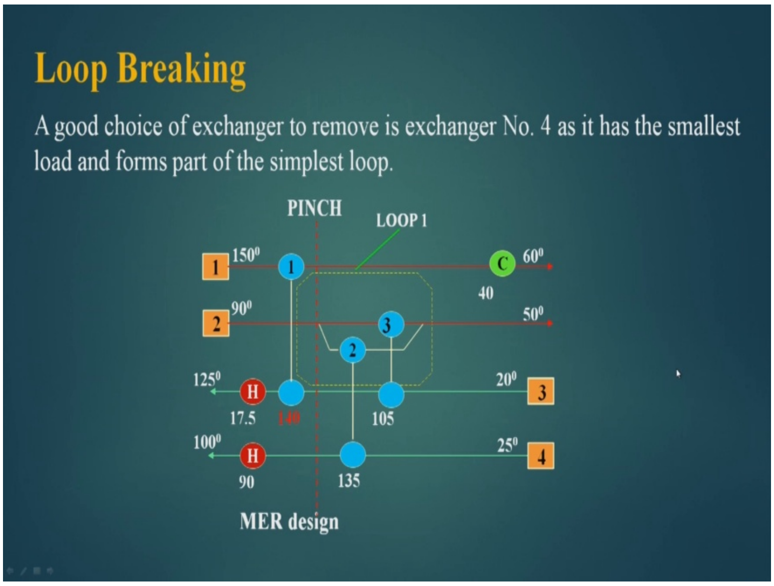


So, if I remove this heat exchanger then its capacity has to be added to this. So, this becomes 140, after transferring.

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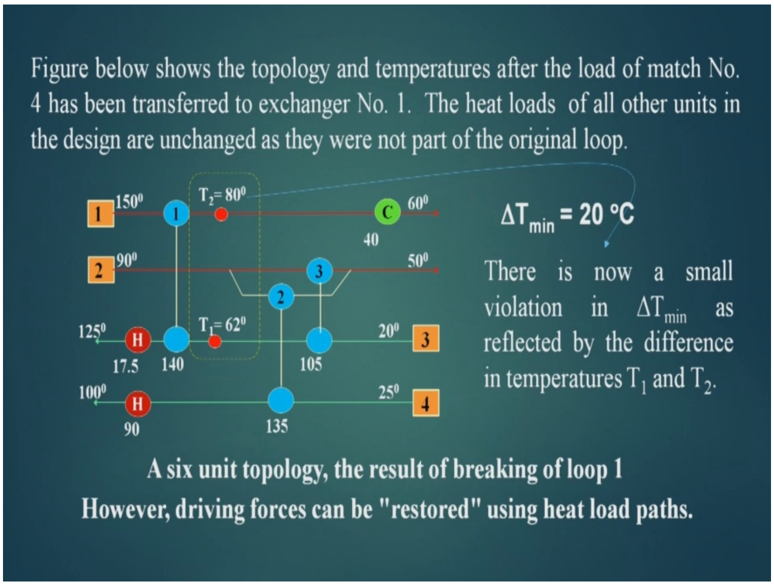


So, this is 140, I have removed a exchanger from here. So, figure below shows the topology and temperatures after the load of match number 4, the heat loads of all other units in the design are unchanged as they were not part of original loop. Now if I see this then here the temperature becomes 62 degree centigrade, here the temperature is 80 degree centigrade. So, there is the violation of delta T minimum criteria. There is now a small violation in delta T minimum as reflected by the difference in temperature between T 1 and T 2. Now if the delta T minimum is violated, obviously this will require different amount of hot utility and cold utility. Now we have to restore this delta T minimum somehow. However, the driving forces can be restored using heat load path. So, what do we have to do, we have to transfer increase the heater capacity, and this will heat will flow this heat exchanger to this cooler, through a heat load path.

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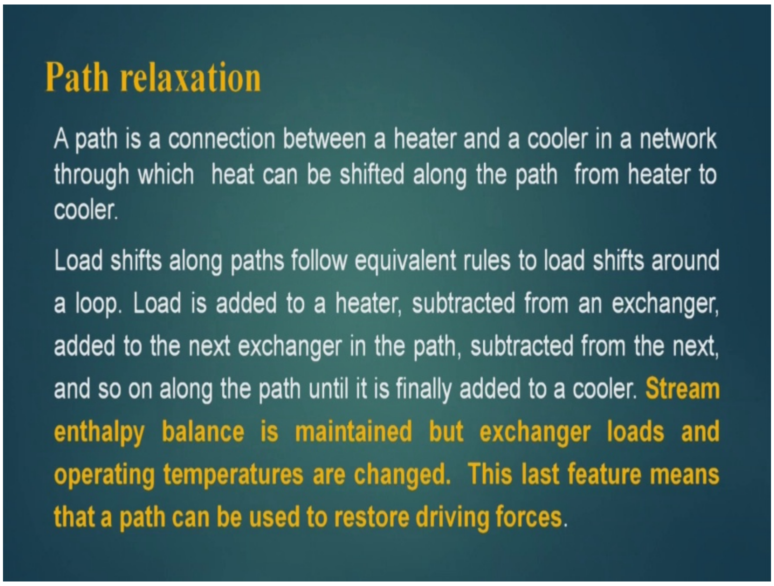


Let us see that what is that path. A path is a connection between a heater and cooler in a network through which heat can be shifted along the path from heater to cooler. Load shifts along path follow equivalent rules to load shift around a loop. Load is added to a heater, subtracted from an exchanger, added to the next exchanger in the path, subtracted from the next and so on along the path until it is finally added to a cooler. Stream enthalpy balance is maintained but exchanger loads and operating temperature are changed. This last feature means that path can be used to restore driving forces.

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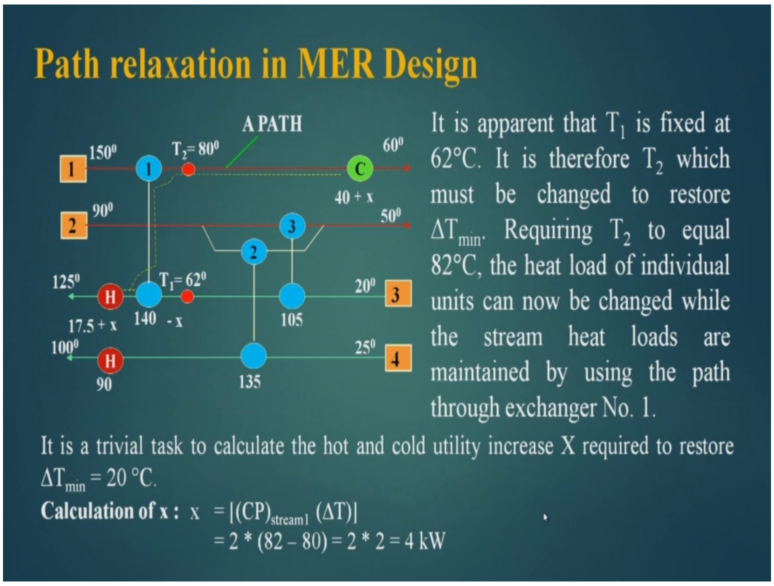

Let us see how it does. Now, here my path is this. Now if I increase the heater capacity from 17.5 then what will happen, you need you have to decrease the load of this heat exchanger to maintain this temperature. And once I decrease the load of this heat exchanger then the heat which I take from this hot stream will decrease. And once it decrease, temperature will increase. And once it increase, I can maintain a delta T of 20 degree. So, when I decrease the heat from here and obviously, heat flows to this cooler and I have to increase the size of the cooler; that means, capacity of the cooler. So, the capacity of this heater increases, the capacity of this heat exchanger decreases and the capacity of cooler increase.

So, in this path, if I am increasing the capacity of the heater by x amount then I have to decrease the capacity of this heat exchanger number 1 by x amount and then I have to increase the capacity of this heat by x amount. So, alternately here, I am adding, here I am deducting, here I am again adding. So, alternately, I have to add and decrease and then I have to find out what should be the value of x, so that this delta T minimum is restored. Now to bring this restore this delta t minimum, I have to make this T 2 temperature as 82 degree centigrade. If I do this, delta T minimum of 10 degree centigrade will be restored here. So, here I am adding x, here deducting x and then adding x here.

Now, it a trivial task to calculate the hot and cold utility increase amount X require to restore delta t minimum equal to 20 degree centigrade; that means, what should be the value of X, which will make this T 2 82 degree centigrade. Now if I do this calculation then x is equal to CP of stream 1 into delta T, this is 2 degree because this delta T is not between these two. This is I want this temperature 82. Now it is eighty, so eighty two minus eighty is equal to two, so it is that delta t. So, this is that delta T, eighty two minus eighty that is that delta t. And this 2 is the CP value here of this stream number one. So, it makes it 4 kilowatt; that means, if I add four kilo watt to this, subtract 4 kilowatt to this, and add 4 kilowatt to this, this temperature will rise to 82 degree centigrade.

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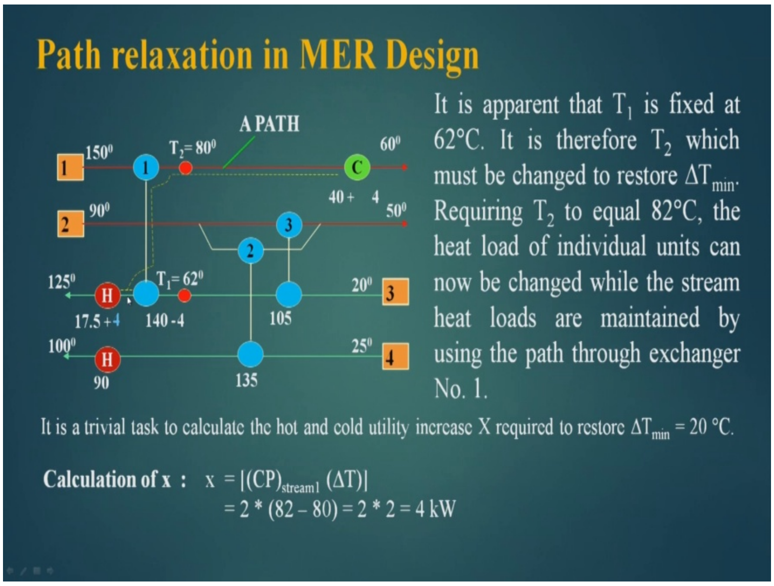


So, let us see this 4 goes there. So, now the capacity of this heater, cooler and this heat exchanger are changed.

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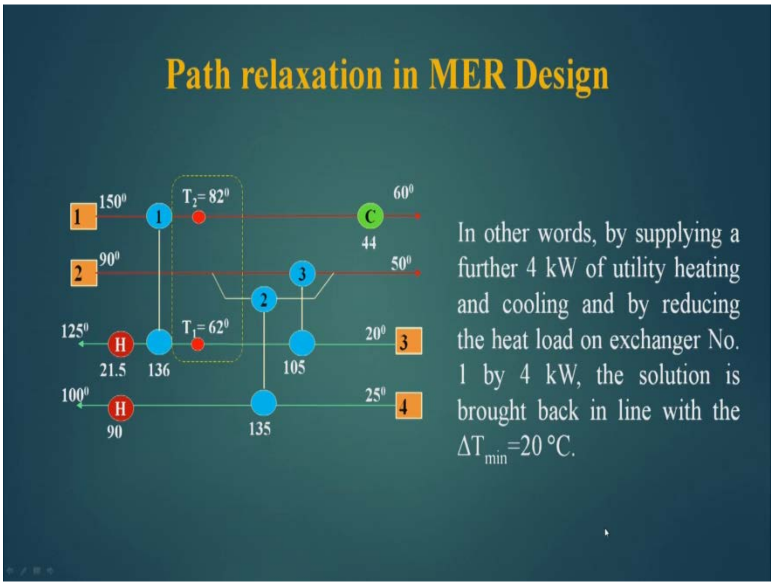


And then this temperature becomes 82 and this are changed capacity. So, in other words, by supplying a further a 4 kilowatt of utility heating and cooling and by reducing the heat load on exchanger number one by 4 kilowatt, this solution is brought back in line with the delta T minimum 20 degree centigrade.

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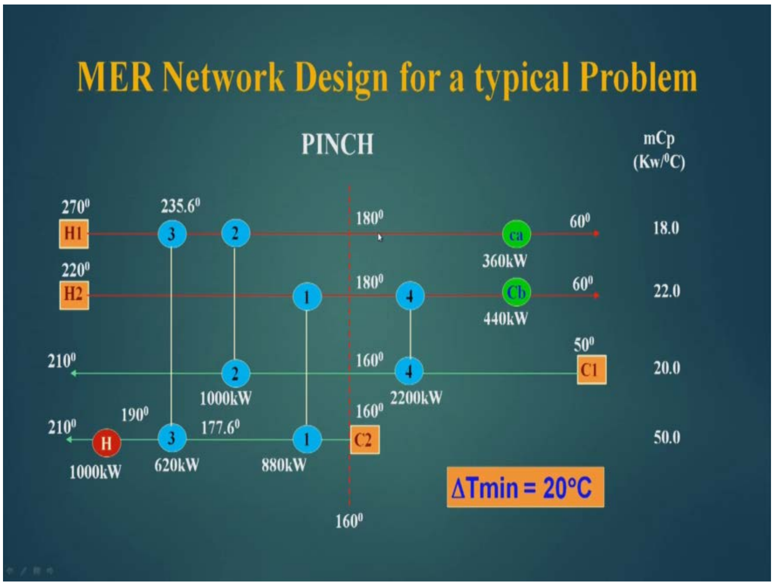


So, we have see that we are able to decrease a heat exchanger by breaking one loop. Similarly, we can also break the second loop and decrease the heat exchanger cost or the number of heat exchanger by one, so that we reach the minimum heat exchanger level that is seven in non-MER design. In the last design, the heat is passed through the pinch and thus after the loop breaking, the design coverts to the non-MER design.

Now we take a another example, where we will see that the loop breaking is not always profitable. The value of X, which comes out due to the loop breaking and restoration of delta T is sometimes very high, and that is why it increase the operating cost a lot and savings in the size of heat exchanger is not that much and that is why it is not always profitable. I had already told you that we will only go for the loop breaking or covert the MER design into a non-MER design, only if there is a trade-off, and we are moving in the path of profit making, otherwise we will not go.

So, let us take an example where we will show you that it is not always advisable to go for a loop breaking. This is the design we are operating on already available design, and this is MER design where delta T minimum is 20 degree centigrade and this is the pinch. There is the heater and there are two cooler here, and there are four number of heat exchangers. So, we will apply here and see whether there are loops and we will try to break a loop.

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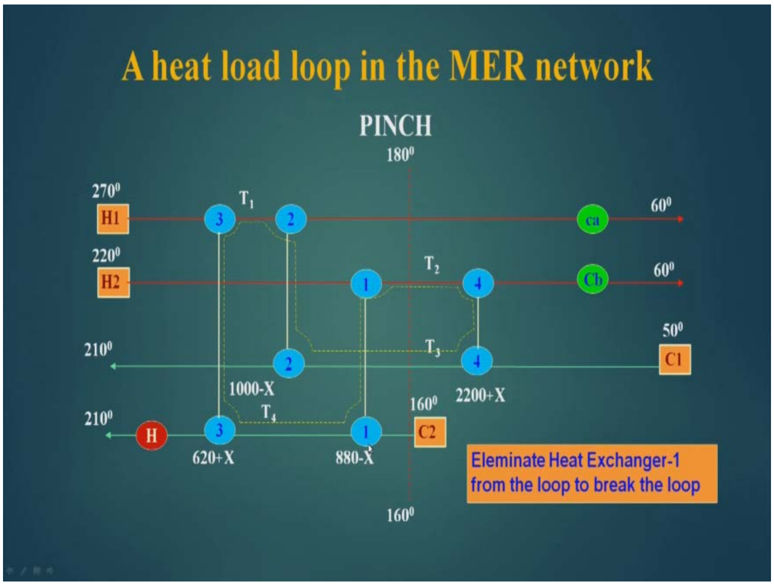


Now this is the loop, which is available here. So, we can start from here, we can go to this, then this, then this and come back, then go to this, then go to this, then go to this and then come back to the same place. This is the loop and we want to break this loop. Eliminate heat exchanger 1 from the loop to break the loop, because this is 880 minus X. So, if I put X is equal to 880, so this heat exchanger will have a size a capacity of zero kilowatt, and this will break. Now once this has been broken, the other heat exchangers will change the capacity will change and we can calculate that. So, if I put X is equal to 880, this becomes zero. This becomes 620 plus 880, this becomes 1000 minus 880, this becomes 2220 plus 880. So, how the size or the capacity of the heat exchanger will change if I put X is equal to 880. Then we will find out a path through which we will pass heat to maintain the delta T minimum.

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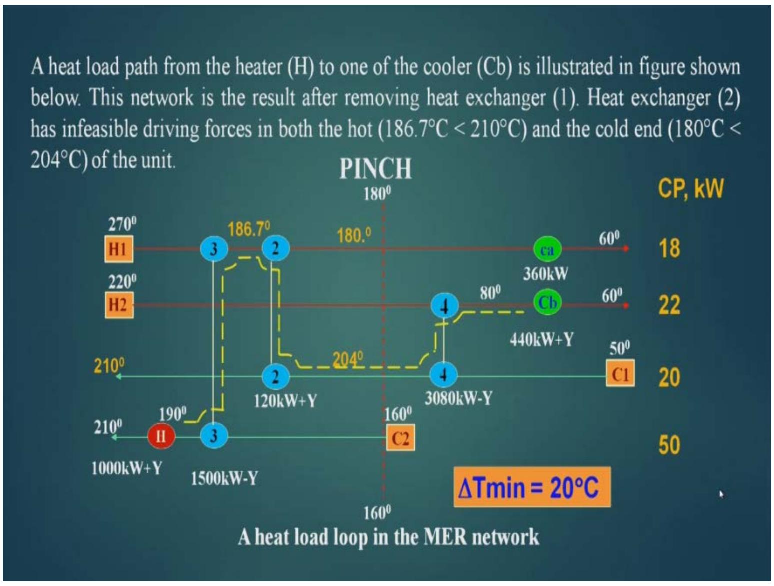


Now we have added the capacity to all these heat exchangers. Now a heat load passes from the heater H to one of the cooler C b is illustrated in the figure. This is the heat path, which we will be using. This network is the result after removing the heat exchanger 1, the heat exchanger 2 has infeasible driving force. If you see here, driving force is infeasible. This is hotter, this is cooler, this is cold is hotter, this is cooler, so these are infeasible driving forces. So, this temperature has to be increased over and above this value, so that the heat flows from here to here, here to here. So, through this path, heat load path, we will increase.

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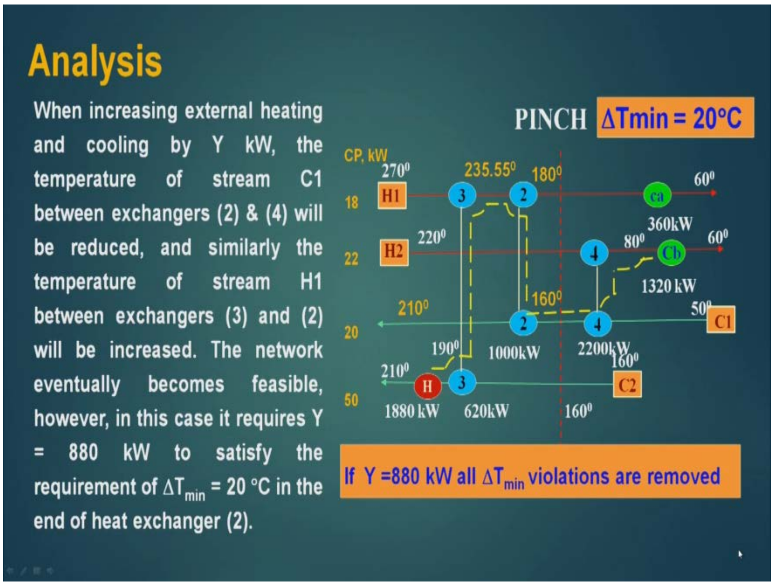

When increasing external heating and cooling by Y kilowatt, the temperature of stream C 1 between exchangers 2 and 4 will be reduced, and similarly the temperature of stream H 1 between exchanger 3 and 2 will be increased. The network eventually becomes feasible, however, in this case it require Y equal to 880 kilowatt to satisfy the requirement of delta T minimum equal to 20 degree centigrade. So, when I increase this capacity of the heater by Y amount, automatically the capacity of this heat exchanger decreased by Y amount. But while we are doing so this temperature remains constant, because I have decreased here I have increased. So, I have decreased heating here, I have increased the heating of same amount here. So, this temperature remains same.

But when I decrease this, I am taking less heat from this hot stream, so this temperature will rise, this temperature will rise. Here the capacity is increasing, so here there will be a drop, or it will maintain same. I have taken Y amount here, I have added Y amount here, so this temperature remains same. But when you decrease this capacity of this heat exchanger, this temperature will change, in such a way that this delta T are restored. So, if I take Y equal to 880 kilowatt, all delta T minimum violations are removed. So, this become size Y becomes 880, so this size increases to 1320 kilowatt. Now this size increases to 2200 kilowatt, and this size increases to 1000 kilowatt, this size to increases to 620 kilowatt, and this increases to 1880 kilowatt. And this temperature will now change, this increases to 235.55 and this decreases to 160.

So here there is a temperature difference of 20 degree centigrade now, and here there is a temperature difference of above 25.55 centigrade now. So, all delta T minimum violations are removed, If I pass 880 kilowatt of energy. And here we will see that the heater capacity is increased by 880, and this cooler capacity has also increased by 880. So, my utility cost has increased twice; that means, 2 into 880 kilowatt of utility cost has increased. And we have to also increase the size of this heat exchanger to pass those utility. Now what I gained is that I am able to remove one heat exchanger of 880 kilowatt.

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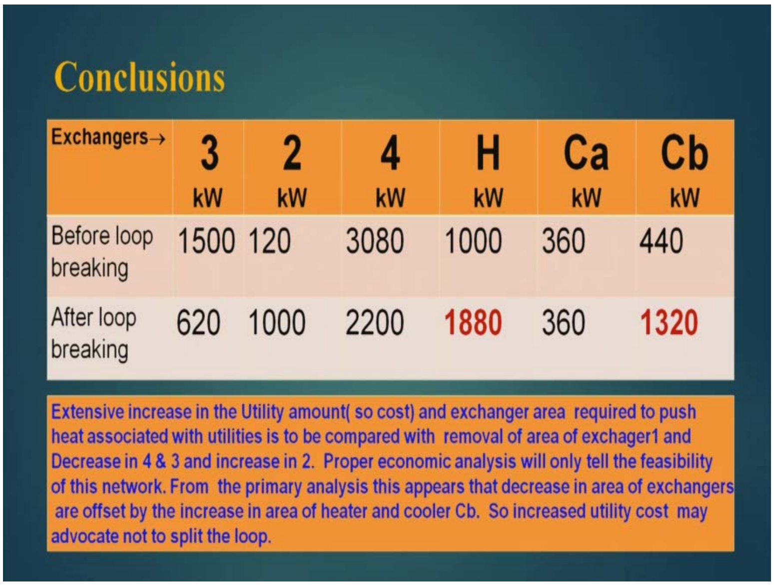


So, let us see that what we have gained, and what we have lost. Now this is the table, which shows a exchanger 3, 2, 4, and this is heater, and these are two cooler. Before loop breaking, this was 1500, this was 120, this was 3080, this was 1000, this was 360 and this is 440. After the loop breaking, its size decreases to 620; but its size increase to 1000; its size decreases to 2220; but its size increase to 1800, this remain same and the size increases to 1320. Now this is the conclusion. Extensive increase in the utility amount so the cost the exchanger area required to push heat associated with utility is to be compared with removal of area of exchanger 1 and decrease in 4 and 3. 4 and 3 area is decreased, but the twos area has increased. Proper economics analyses will only tell the feasibility of this network. From the primary analyses this appears that decrease in the area of the heat exchanger are offset by the in increasing the area of the heater and cooler.

So, there are three heat exchangers, where the area has been increased by 880, there are two heat exchangers, where it have decreased by 880, and one heat exchanger which was removed whose capacity was 880. So, three have increased, and three have decreased. So, as far as cost is concerned, fixed cost is concerned, they have nullified each other. But the operating cost has increased by 2 into 880, because the utility cost has been increased. So, increased utility cost may advocate not to split the loop. So, what we see that there is a chance that the economic will not favor this split. So, what conclusion we make that always we will not find that removing of heat exchanger by splitting the loops is always advisable.

So, when we are decreasing the number of unit; that means fixed cost, there will always will be increase in utility cost. And we have to very trickily balance this, and for this a economical analyses has to be done. So, if the economic will tell that go for splitting and go for removing the heat exchangers by converting the design from MER to non-MER, then we will go for it; and if the economic do not permit it, we will not go for it. So, it is not that a non-MER design will always be better than the MER design, because it decreases the number of units.

Thank you.