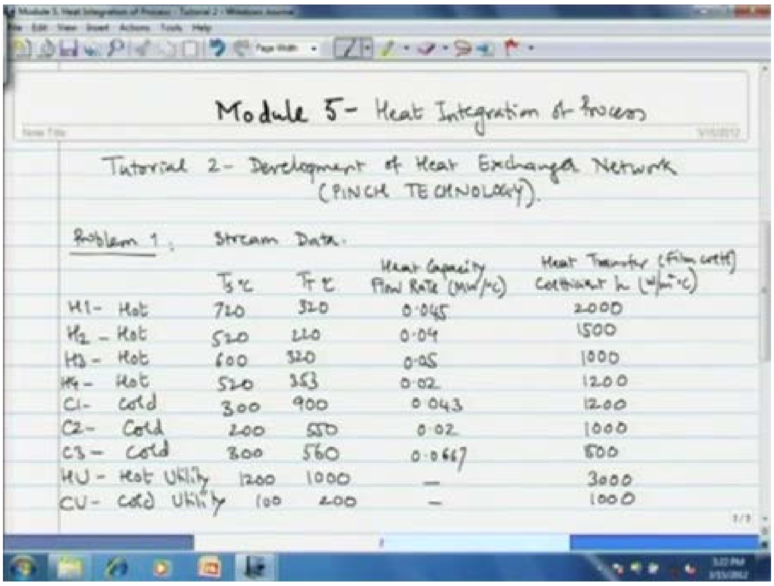
Process Design Decisions and Project Economics

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

Module - 5
Energy (or Heat) Integration of the Process
Lecture - 28
Heat Exchanger Network Synthesis Using Pinch Technology

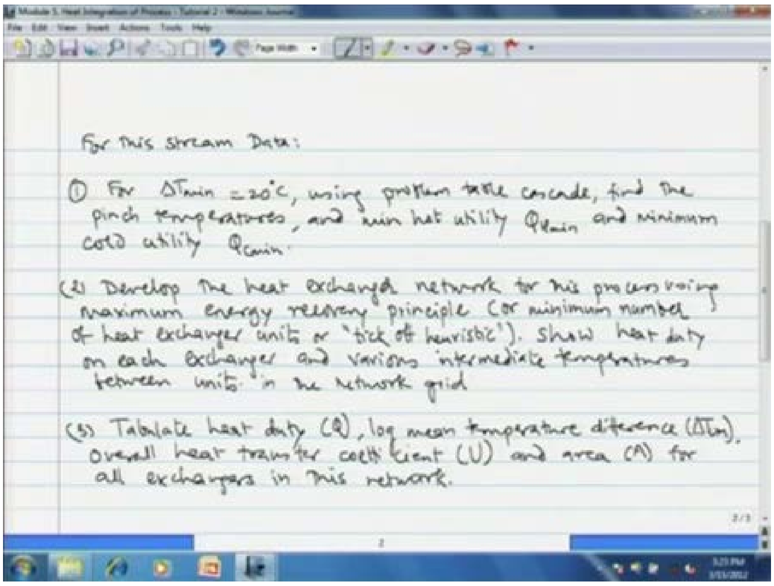
(Refer Slide Time: 00:25)



Welcome, today we will have the second tutorial of the module of heat integration of the process. Topic for today's tutorial is development of heat exchanger network or pinch technology. So, let us see the first problem of today's tutorial, we have been given stream data, that is now appearing on your screen. We have total of four hot streams and three cold streams plus one hot utility and cold utility. The supplied target temperatures T 1 and T T are also listed like the first hot stream has the supplied temperature of 720 degree centigrade target temperature of 320, the heat capacity flow rate is 0.45 megawatt per degree centigrade. It has a heat transfer coefficient are also known as film coefficient of 2000 watt per meter square per degree centigrade.

Similarly, H 2 has supplied temperature of 520, target temperature of 220, heat capacity flow rate of 0.04 megawatt per degree centigrade and heat transfer coefficient of 1500. Similarly, you can see the other temperatures, the hot utility has supplied temperature of 1200 degree centigrade. It is the high temperature process and target temperature is 1000 degrees. The heat transfer coefficient is 3000 watt per meter square per degree centigrade, and the cold utility has supplied temperature of 100 degrees and target temperature of 200 degrees and its coefficient is 1000 watt per meter square per degree centigrade.

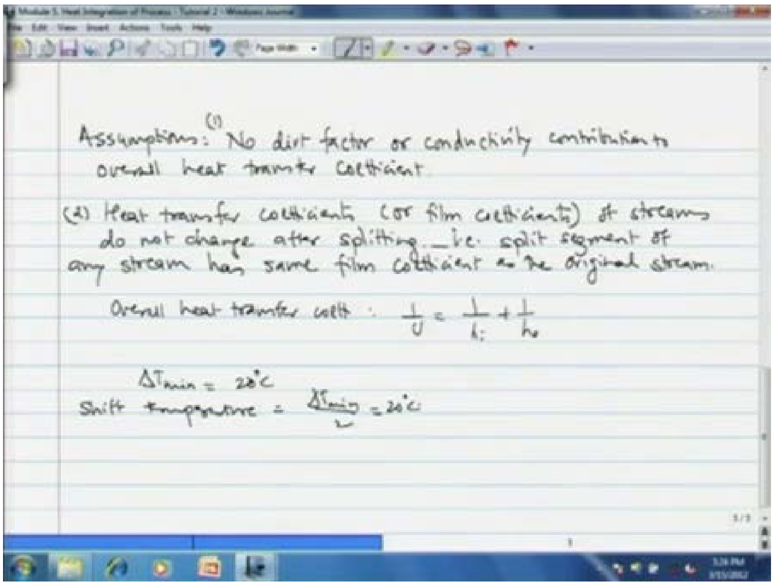
(Refer Slide Time: 02:01)



For this stream data we have to answer three questions; first is that for delta T mean equal to 20 degree centigrade, we have to find the minimum hot utility and minimum cold utility, as well as the pinch temperature using problem table cascade. Then the second question is the development of the heat exchanger network for the process using maximum energy recovery principle or minimum number of heat exchanger unit or what is known as tick off heuristic; that we have seen in the theory lectures.

We are also supposed to show the heat duty of each exchanger and a very intermediate temperature between in its, in the exchanger or a network grid. Third question that we have to answer is tabulation of heat duty, log mean temperature difference, overall heat transfer coefficient and area for all exchangers in the network. So, we have to develop that data process rate of our all the exchangers that we will design.

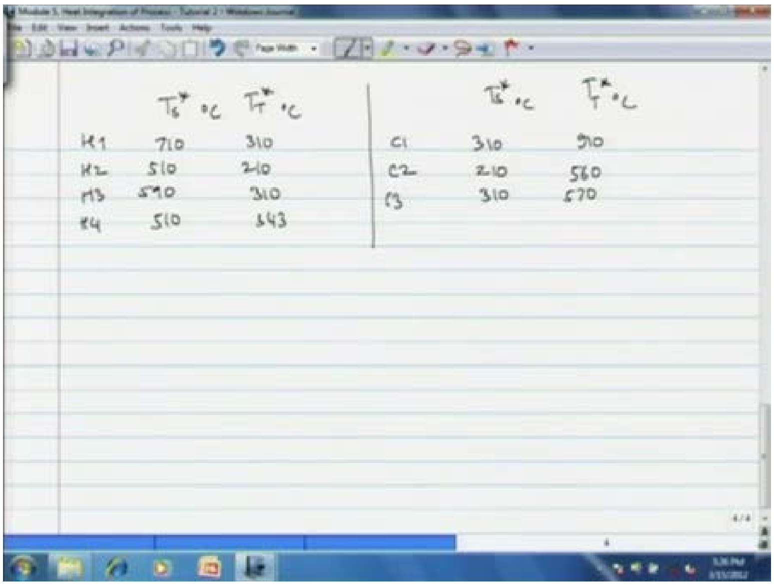
(Refer Slide Time: 03:08)



We can make two assumptions in the solution; first is that there is no dirt factor or conductivity contribution to overall heat transfer coefficient or we can say that overall heat transfer coefficient is given by 1 by U is equal to 1 by h i plus 1 by h inside heat inside film coefficient plus outside film coefficient, there is a reciprocal of those. Then the second assumption that we are going to make, is that the heat transfer coefficients or film coefficients of the streams do not change after splitting.

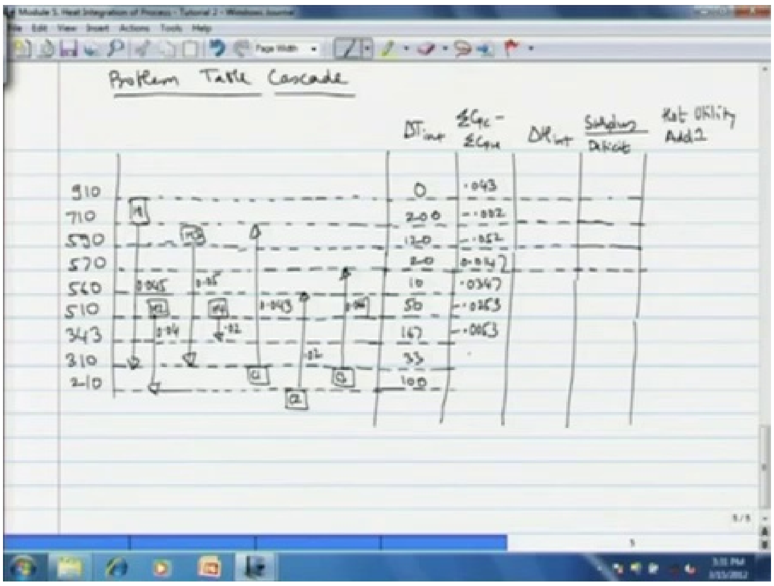
That is the split segment of any stream has same film coefficient as the original stream. So, with these two assumption we start our calculation. Now, we have seen two examples of problem table cascade in previous tutorial, so I will go rather quickly over it we have been given delta T mean equal to 20 degree centigrade. So, we have to shift the temperature of the streams by delta T mean by 2 that is 20 degree centigrade. Now, I will directly show the problem table cascade.

(Refer Slide Time: 04:33)



h 1 is shifted temperatures supplied temperature T s star is 710 degree centigrade, shifted target temperature is 310, 10 degrees decreased. Then h 2 510 and 210. h 3, 590 and 310. h 4, 510 and 343 all. Temperatures decreased by factor of 10, then the cold stream temperatures. Now, here we have to increase the temperature by 10 degree centigrade. So, C 1 supplied temperature become 310, target temperatures become 910, C 2 supplied temperatures become 210 target temperatures become 560. C 3 supplied temperature is 310 and target temperature is 570. With this we now construct the problem table cascade as we did in earlier example.

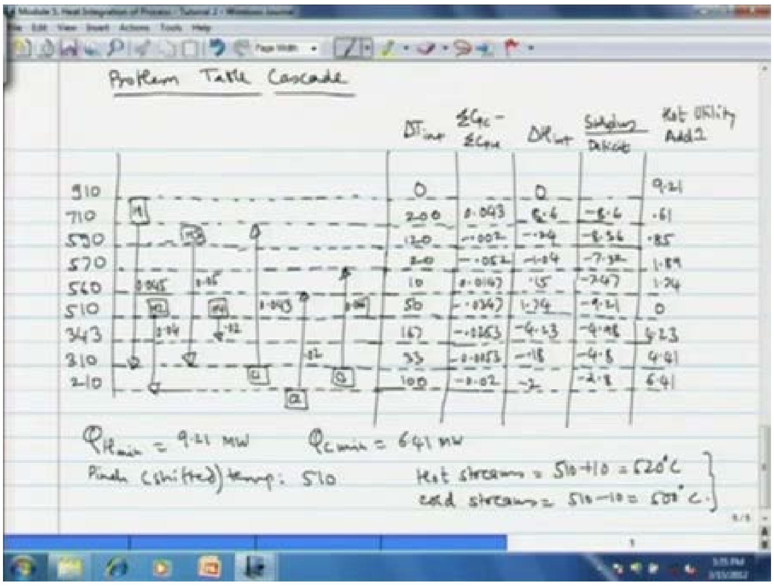
(Refer Slide Time: 05:52)



I will list, I will list all the shifted temperature intervals in the decreasing order and then we shall show the stream population between these temperature intervals. The stream h 1 goes from 710 to 310. It has a c p of 0.045, then h 2 goes from 510 to 210. Then h 3 goes from 590 to 310. Then h 4 goes from 510 to 343 plus c p failures I am listing. Now, h 2 0.4, h 3 point sorry, 0.04 not 0.4. h 3, 0.05, h 4 0.02. Then similarly, for C 1, C 2, C 3 the cold streams C 1 goes from 310 to 910 with heat capacity flow rate of 0.043, C 2 goes from 210 to 560 with heat capacity flow rate of 0.02.

C 3 goes from 310 to 570 with c p of 0.0667. Now, we have to list the delta T interval and summation C p C minus summation C p h for that particular interval summation of the heat capacity flow rates for cold stream minus summation of the heat capacity flow rate for hot stream. Then delta h interval, then we have to find whether the interval has surplus or deficit of heat. Finally, the after hot utility addition the surplus deficit, now I will directly list the values we have seen in the calculations before. Then calculation of this detailed calculation of the problem table cascade am leaving as an exercise for you, delta T interval 0, 200, 120, 20, 10, 50, 167, 33 and 100. Then summation C p C minus summation C p h 0.043 minus 0.002 minus 0.052, 0.0147 sorry, 0,0147, then 0.0347 minus 0.0253 minus 0.0053.

(Refer Slide Time: 11:44)



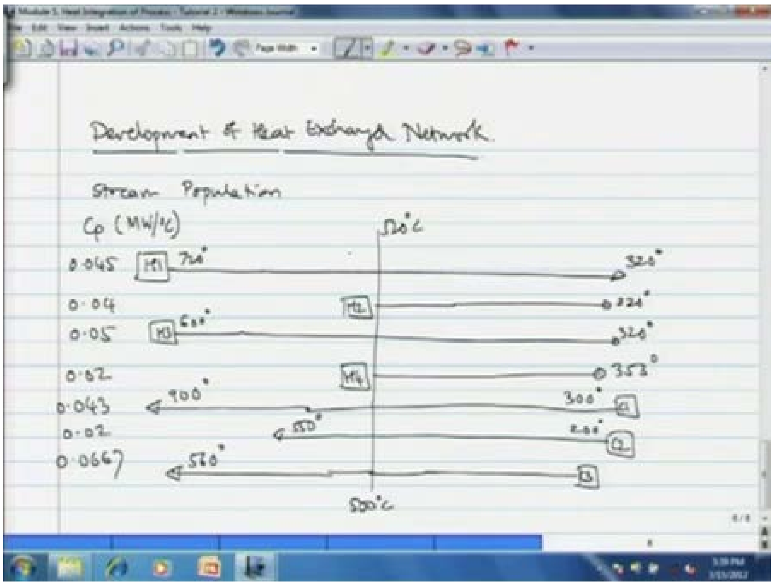
So, that is summation C p C summation C p h and then when we multiply delta T interval and that we get delta h interval. So, that values also I am going to write, now 8.6

minus 0.024 minus 1.04, 0.15, 1.74 minus 12.23 minus 0.18 minus 2. Then we have to see surplus deficit like in the first interval, we have deficit so minus 8.6. Then minus of minus 2.24, so minus 8.36 and solving so on and so forth.

Again I am giving the direct values. I will leave the calculation as an exercise. Then we see that the maximum negative are delta h are maximum deficit occurs in the interval of 5625 and 10 as minus 9.21 megawatt. We add that much off hot utility and then everything balances off we get pinch at temperature of 510 where the total delta h becomes 0. Thus after all solution, we are left with 6.41 megawatt to be removed by cold utility. So, we have the answers with us now, q h min is equal to 9.21 megawatt and q C min is 6.41 megawatt.

The pinch temperature shifted temperature is 510 that is for hot streams. The temperature is 510 plus 10; that is 520 degree centigrade and for cold streams the temperature is 510 minus 10, which is 500 centigrade. So, these are the pinch temperatures, now with this information, so we have answered the first bit of the problem; that is development of problem table cascade and determination of q h min problem. That is development of problem table cascade and determination of q h min and q C min. Now, we go to the second bit of the problem that is development of heat exchanger network using maximum energy recovery principle.

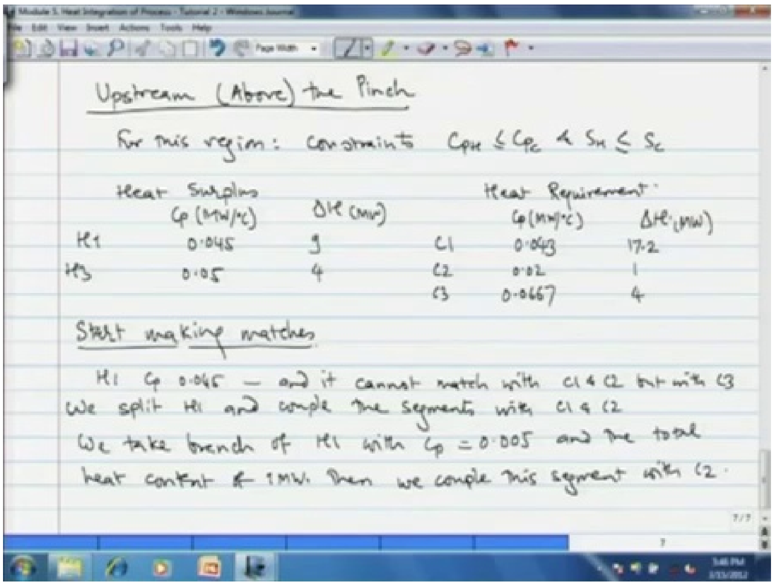
(Refer Slide Time: 15:36)



Now, to do that we first write the stream population as we just determined the pinch occurs at 520 degree centigrade for hot streams and 500 degree centigrade for cold stream. Then we list the C p values here h 1 goes from 720 to all the way 320 degrees. Then h 2 is has heat capacity of 0.04. h 2 goes from 520 to 220. Then h 3 goes from 600 to 320 with c p value of 0.05.

Then h 4 again goes from 520 to 353. It has a heat capacity flow rate of 0.02. Then C 1 goes from 300 degree centigrade to 900. It has a c p of 0.043. C 2 goes from 3 200 to 550 it has a c p value of 0.02 and C 3 goes from 300 to 560 with c p value of 0.0667. Now, we have at a glance the stream population and what are the streams and what temperatures? They are going above and below the pinch, now we first consider the upstream region of pinch. So, there we shall start our problem upstream or above the pinch.

(Refer Slide Time: 19:01)



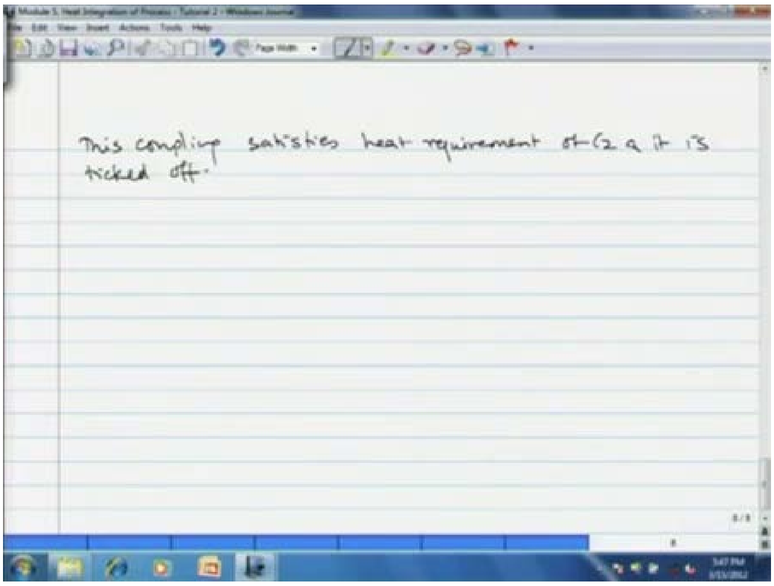
Now, above pinch we have two hot streams H 1 H 3 and three cold streams. So, let us see what is the heat available with hot stream? And what is the heat requirement of the cold streaming addition for above pinch region? We have some constraints as we have seen in the theory lecture, the constraints are C p h has to be lesser or equal to C p C. Number of hot streams have to be lesser or equal to number of cold streams.

Now, let us see the heat surplus and heat requirement h 1 C p value of 0.045 and delta H is H 1 is going from 720 to 520. So, 200 degrees difference, so 0.045 into 200 is 9 megawatt. So, 9 megawatt are available with h 1. Then similarly, h 3; it as a heat capacity 0.05 and above pinch region is it goes from 600 to 520, so a temperature difference of 80 degrees. So, eighty into 0.045 is 4 megawatt.

So, 4 megawatts are available with h 3, the heat requirement C 1 has heat capacity of 0.043 and it is going from 300 to 500. So, 200 degrees jump and then the delta h that is required is 17.2 sorry, we are considering above pinch region, so C 1 is going from 500 degrees to 900 degrees, so 400 degrees jump. Therefore, the delta h is 17.2 megawatt requirement, heat requirement of C 1. Then C 2 is going from 500 to 550. It has a C p value of 0.02, so 0.02 into 50 is 1 megawatt.

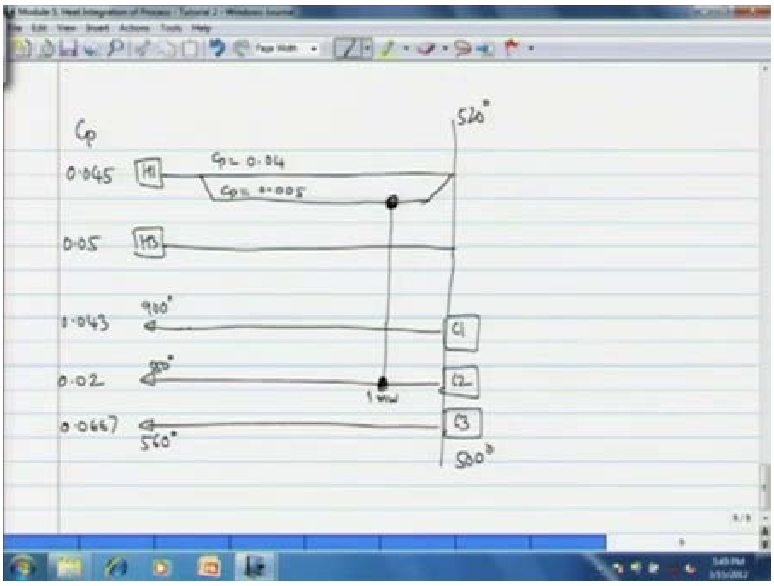
C 3 has heat capacity flow rate of 0.0667 and it is going from 500 to 560. So, 60 degrees jump and therefore, it has delta h of 4 megawatt or heat requirement of 4 megawatt. Now, we have to start making matches, we have the constant of C p h lesser than C p C. Now, H 1 can match H 1 has a C p value of 0.045. It cannot match with C 1 and C 3, but with C 1 and C 2, but with C 3, however the heat that is available with H 1 is much higher than the heat requirement for C 3. Therefore, what we do is that we split H 1 and couples the segments with C 1 and C 2. Now, we take branch of or split segment of H 1 with C p value of 0.005 and the total heat content of 1 megawatt and then we couple this segment with C 2.

(Refer Slide Time: 24:43)



Now, this coupling satisfies the heat requirement of C 2 and it is ticked off. Now, we start developing the heat exchanger network above.

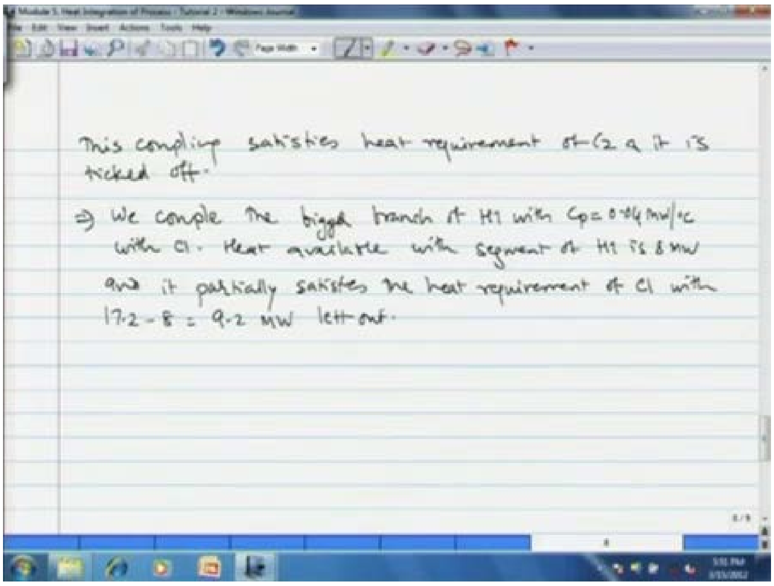
(Refer Slide Time: 25:13)



Pinch 520 degrees hot stream temperature, 520 degrees cold stream temperature C p values I am listing here separately. H 1 stream may just thought of splitting it in a C p of 0.005 and C p of 0.04. Then we are going to couple it with C 1, the smaller segment. But before that I will draw for other streams as well, so that later on we can star just putting the matches.

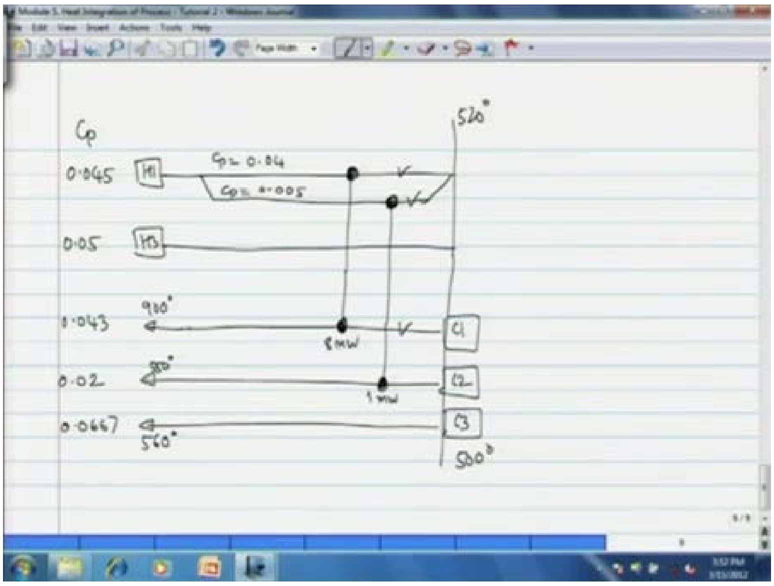
So, we just made the first match of coupling the smaller branch of H 1 with that of C 2. We write here the heat load on this exchanger 1 megawatt. Now, the next we couple sub branch of H 1, which heat capacity flow rate of 0.01 to C 1. So, C 1 has quite high heat load. As we have already seen it requires 7.2 megawatts, so partially it is satisfied through the bigger branch of H 1.

(Refer Slide Time: 27:59)



So, that point we note we couple the bigger branch of H 1 with C p of 0.04 megawatt per degree centigrade with C 1 heat available with segment of H 1 is 8 megawatt. It partially satisfies the heat requirement of C 1 with 17.2 minus 8; that is 9.2 megawatt left out, now we make the second match segment of H 1.

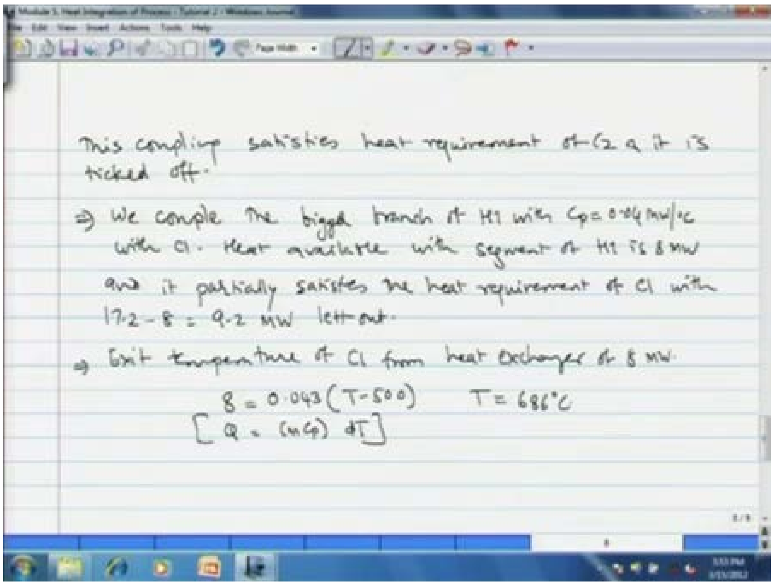
(Refer Slide Time: 29:19)



The bigger segment is matched with C 1 and sorry match with C 1 and heat load here is 8 megawatt. So, the segment of H 1 is now ticked off, okay? C 1 is already ticked off, now H 1 is completely ticked off. Now, we are left with one hot stream and one cold stream.

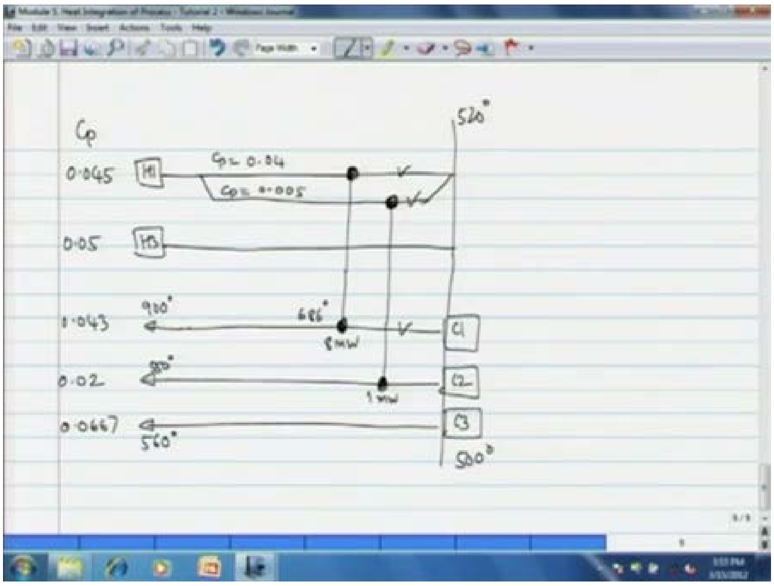
However, the C 1 stream is not fully satisfied, so what we do now is, we determine the temperature of the stream that is emerging from this 8 megawatt exchanger exit temperature of C 1 from heat exchanger of 8 megawatt.

(Refer Slide Time: 30:19)



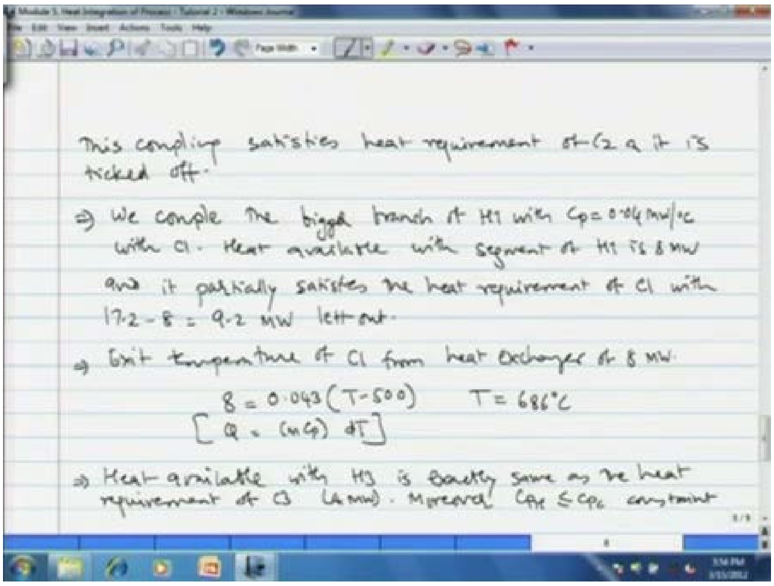
So, we write a simple equation eight is equal to 0.043, the heat capacity flow rate T minus 500 and determine T to be 686 centigrade. So, this is essentially Q is equal to M C p into d T kind of relation. Then we determine the intermediate temperature of stream C 1 as 686 degree centigrade.

(Refer Slide Time: 31:11)



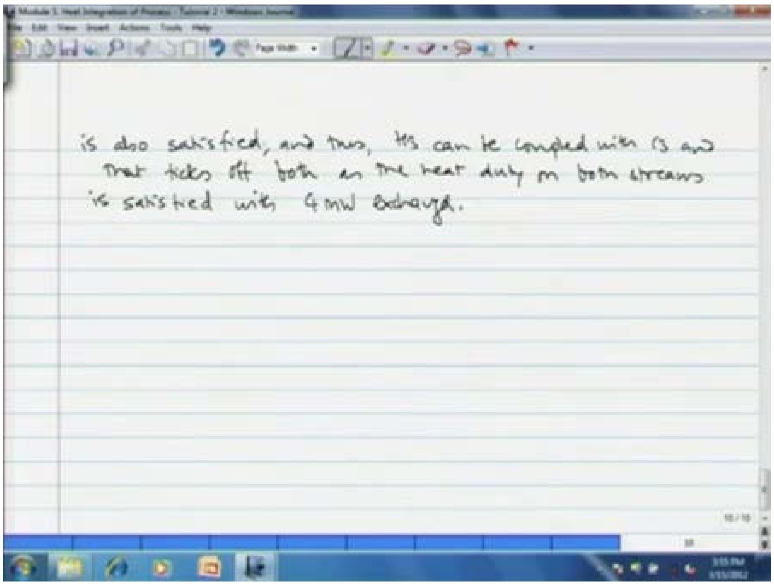
We write it here 686 degree centigrade, now we are left with one hot stream H 3 and second hot stream C 3 second cold stream C 3. Now, if you look at the heat capacity and the requirement H 3 has a heat capacity of 0.05, which is lesser that 0.0667. So, it can be easily coupled and the heat that is available with H 3 is exactly the requirement of C 3. Therefore, H 3 C, C 3 can be coupled that point.

(Refer Slide Time: 32:03)



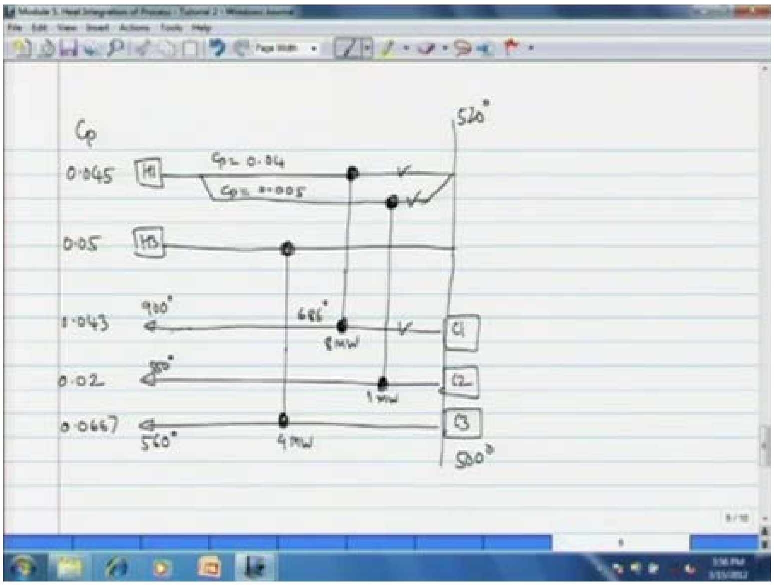
We know heat available with H 3 is exactly same as the heat requirement of C 3; that is 4 megawatt. Moreover, C p h less 1 equal to C p C constraint is also satisfied.

(Refer Slide Time: 32:40)



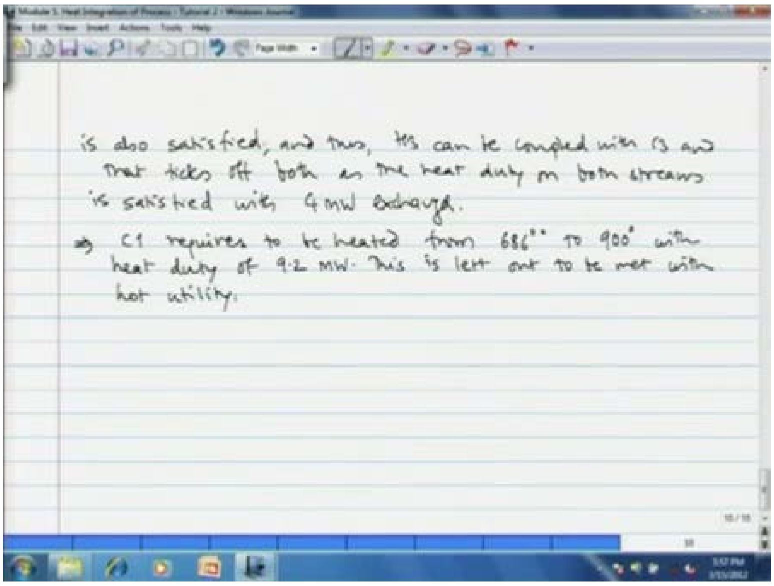
Thus H 3 can be coupled with C 3 and that ticks off both the streams as the heat requirement or the heat duty is satisfied heat duty on both streams is satisfied with 4 megawatt exchanger. Now, the only thing that is left out is the remaining heat duty of C 1. C 1 is emerging at temperature of 686 degree centigrade from 8 megawatt exchanger.

(Refer Slide Time: 33:31)



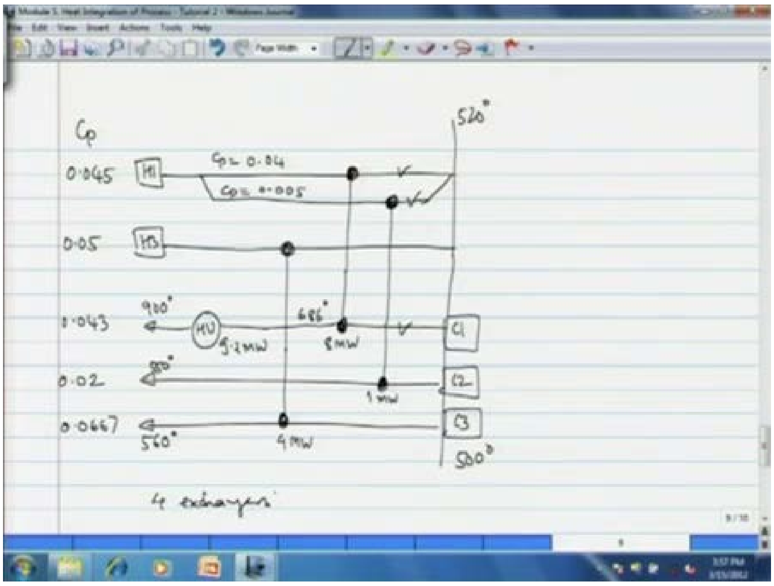
It has to go 900 degree centigrade, the heat that is required is exactly the same as the hot utility that is required 9.2 megawatt, C one requires to be heated from 686 degrees to 900 degrees with heat duty of 9.2 megawatt.

(Refer Slide Time: 34:06)



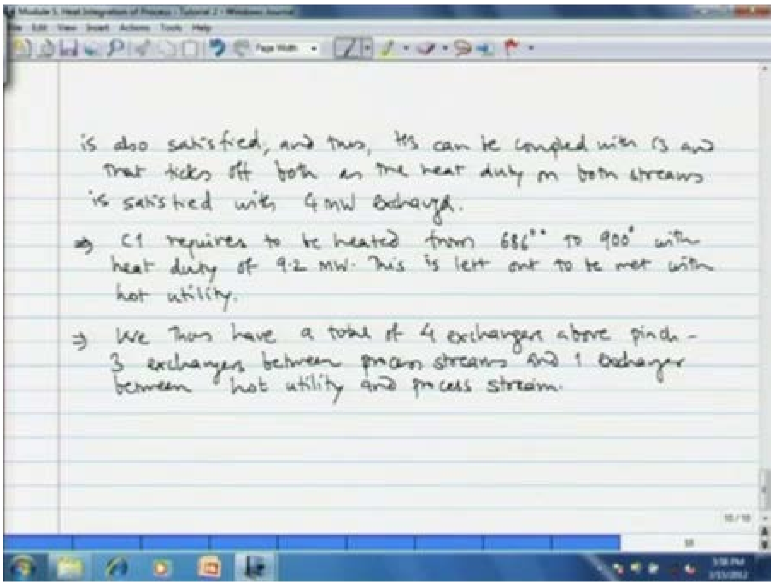
This is left out to be met with hot utility, so we now place the last exchanger here C 1 the hot utility.

(Refer Slide Time: 34:59)



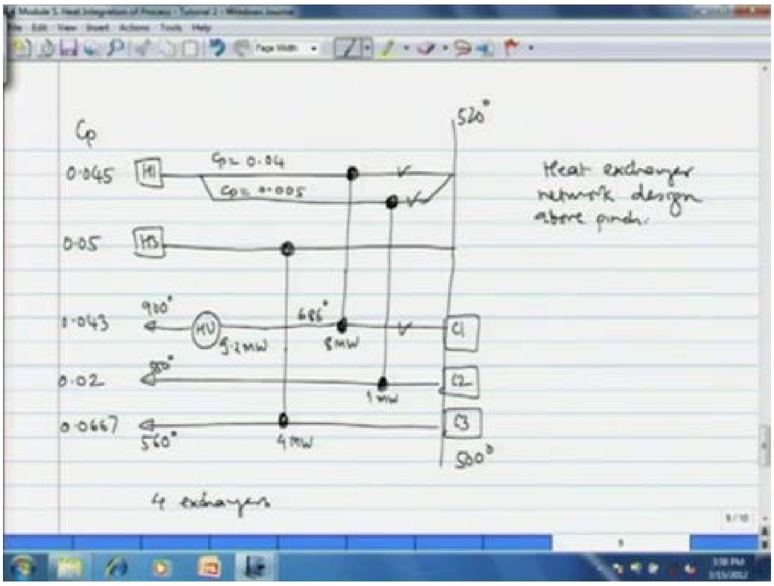
Here the load is 9.2 megawatt, so we have a total of four exchangers upstream; three exchanger between process streams and one exchangers, one exchanger between hot utility and C 1, so that point we note.

(Refer Slide Time: 35:32)



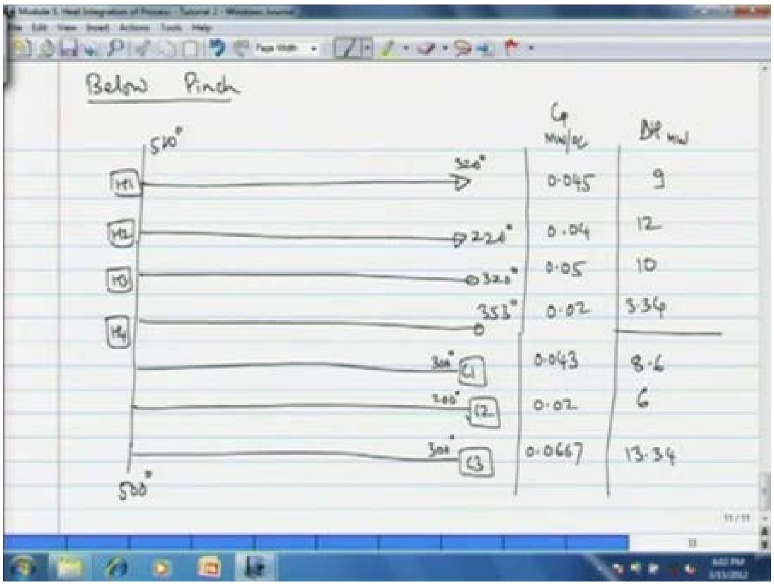
We thus have a total of four exchangers above pinch three exchangers, between process streams and one exchanger between cold utility sorry hot utility and process stream. So, that completes the design pinch design above or the pinch heat exchanger design above pinch.

(Refer Slide Time: 36:30)



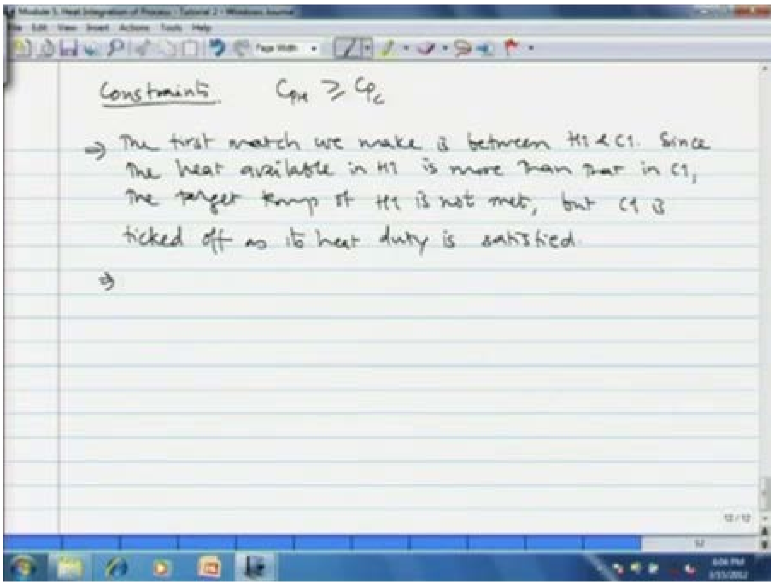
Now, for below pinch region, we again draw a stream population diagram.

(Refer Slide Time: 36:48)



Then we shall see what are the heat sources, what are the heat sinks? So, H 1 goes from 520 to 320, H 2 goes from 520 to 220. Then H 3 goes again from 520 to 320. C 1 sorry, H 4 is also there. H 4 goes from 520 to 353. C 1 goes from 300 to 500, C 2 goes from 200 to 500 and C 3 goes from 300 to 500. I shall also less to the C p values. Delta H, the heat available or surplus with each stream H 1.045, H 2.04, H 3.05, H 4.02, C 1 0.043, C 2.02, C 3 0.0667. Then the delta H megawatt 9 megawatt available, with H 1 12 megawatt available, with H 2 10 megawatt available, with H 3 3.34 megawatt available, with H 4 then 8.6 megawatt required by C 1 6 megawatt required for C 2 and 13.34 megawatt required for C 3.

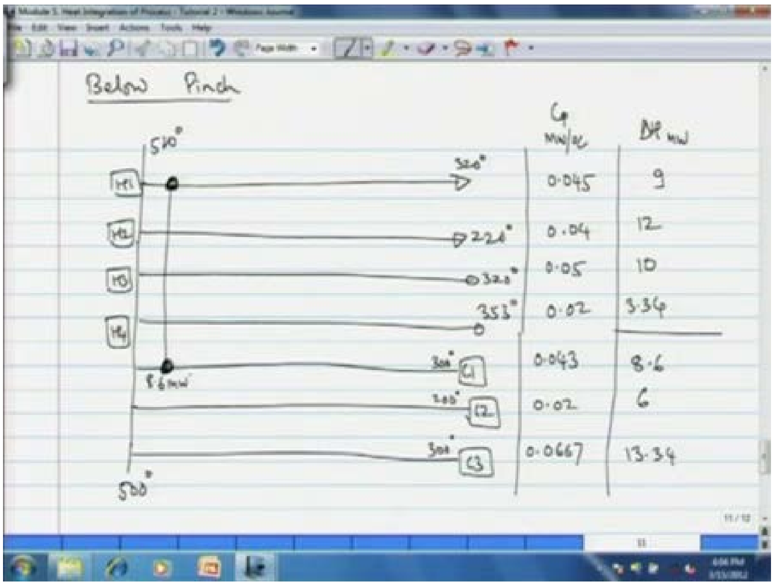
(Refer Slide Time: 39:52)



Now, the constraint that we need to satisfy is that C p h greater or equal to C p C. Now, looking at the H values and the constraint k, we can see that we can match H 1 with C 1 without any trouble because H 1 has higher heat capacity than C 1. Heat, the heat available with H 1 is 9 megawatt and that is required by C 1 is just 8.6 megawatt. So, we can start matching the first match, we make is between H 1 and C 1.

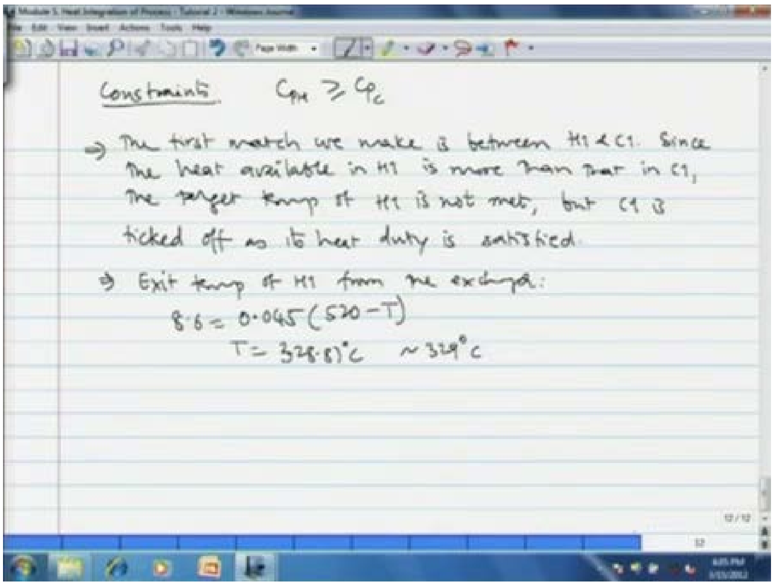
Now, since the heat that is available in H 1 is more than that required by C 1, the target temperature is not reached, but all the heat duty of C 1 is satisfied. So, C 1 is ticked off, since the heat available in H one is more than that required in C 1, the target temperature of H 1 is not met. But C 1 is ticked off as its heat duty is satisfied. Then now we make them first match of below pinch region between H 1 and C 1.

(Refer Slide Time: 42:04)



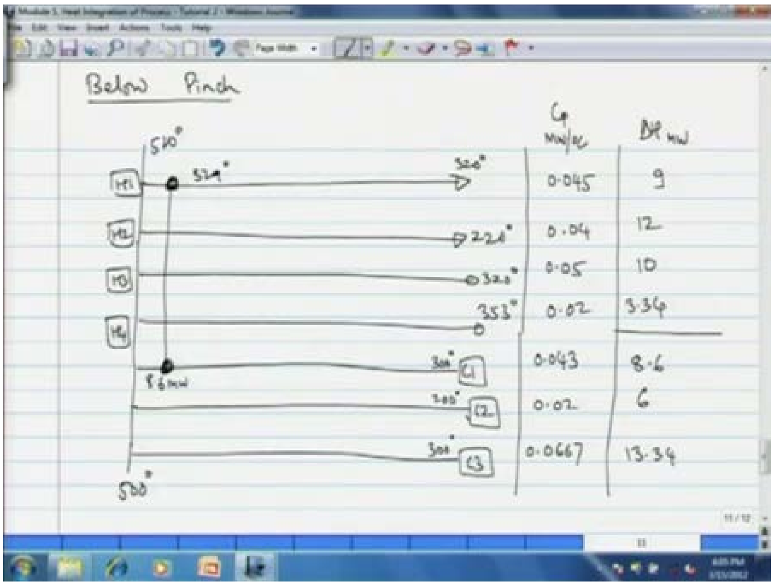
Here we write the heat load that is 8.6 megawatt, but the exit temperature of H 1.

(Refer Slide Time: 42:25)



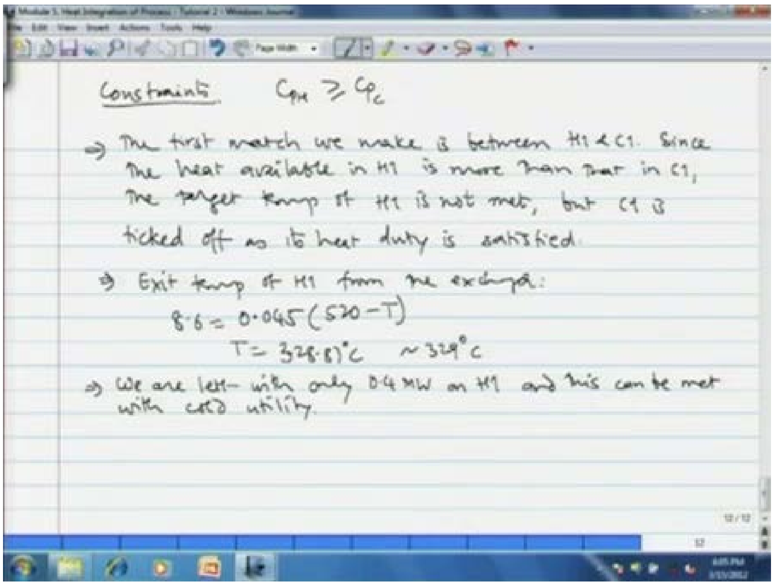
From the exchanger can be again found out with simple formula 8.6 is equal to 0.045 into 520 minus T and T turns out to be 328.87 or we can approximate as 329 degree centigrade and that intermediate temperature we write here 329 degrees.

(Refer Slide Time: 42:55)



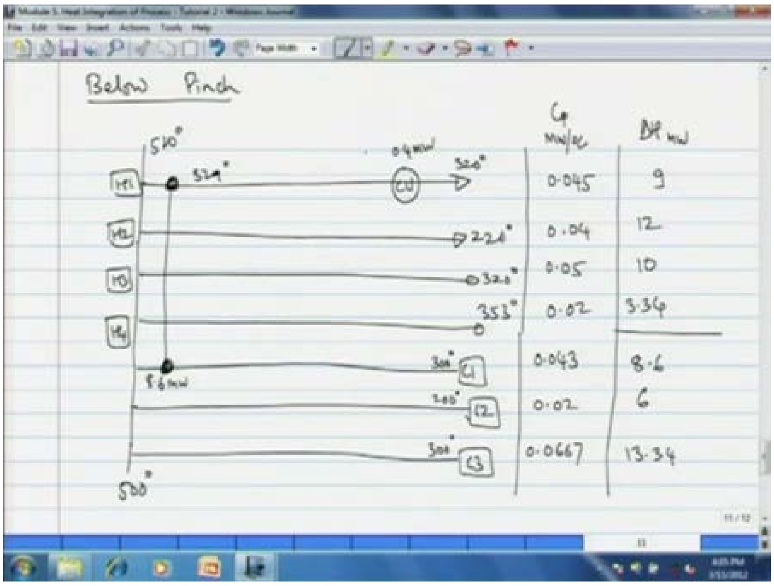
Now, we are left with only 0.4 megawatt on H 1.

(Refer Slide Time: 43:04)



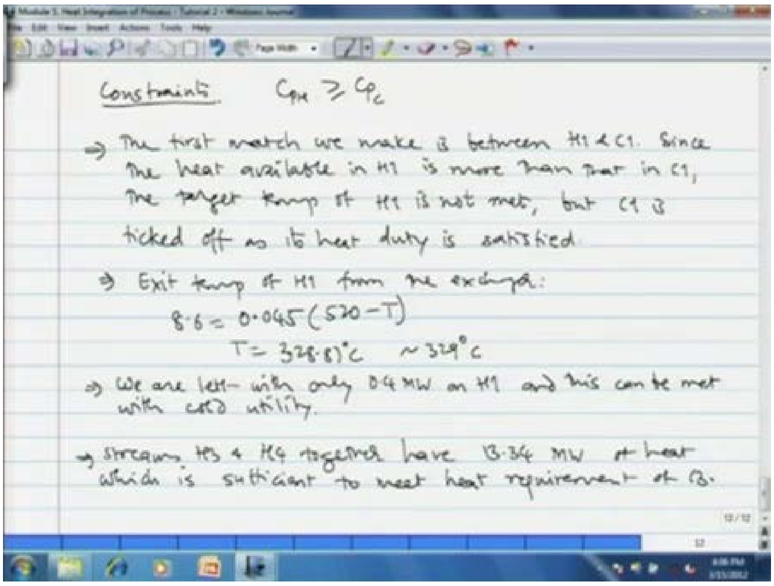
This can be met with cold utility.

(Refer Slide Time: 43:28)



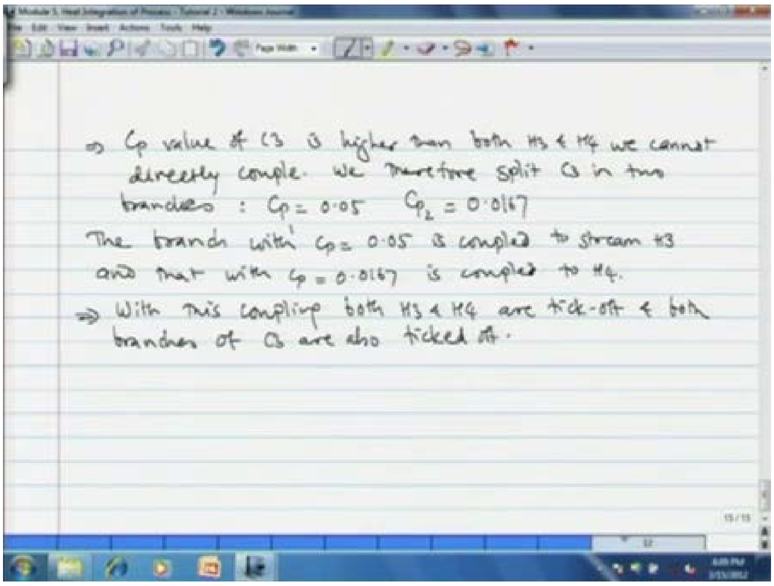
Now, we put the cold utility exchanger here 0.4 megawatt and this ticks off the H 1 stream, because all of its heat duty is satisfied.

(Refer Slide Time: 43:47)



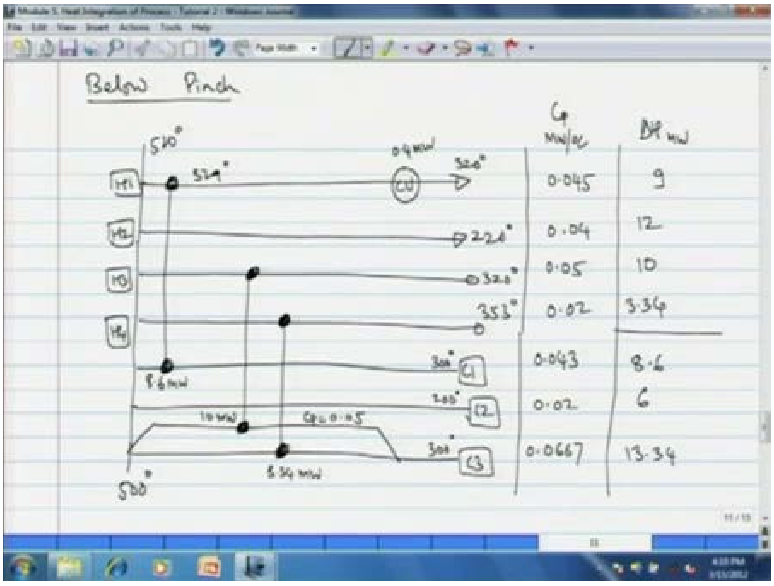
Now, stream H 1 sorry, stream H 3 and H 4 together have 13.34 megawatt of heat, which is sufficient to meet the heat requirement of C 3. However, we are restricted by the C p constraint.

(Refer Slide Time: 44:37)



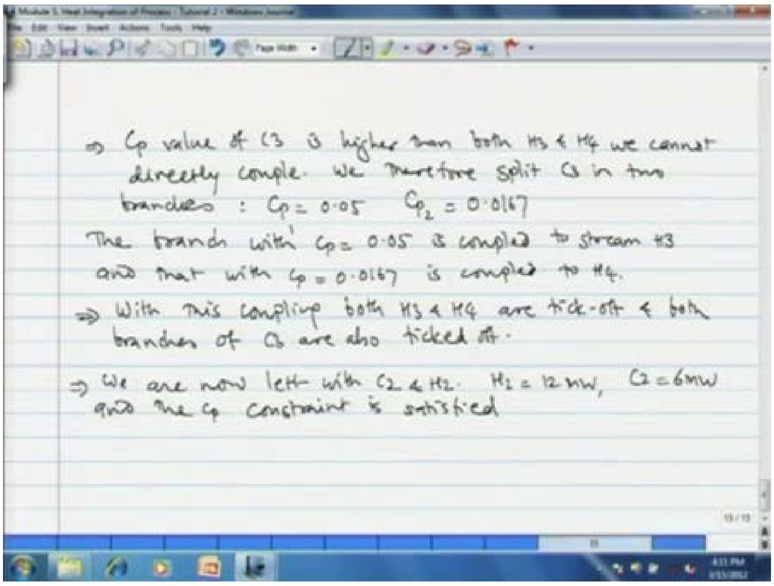
The C p value of C 3 is higher than both H 3 and H 4. We cannot directly couple. Therefore, we go for splitting of seem stream C 3 in two branches; one branch with C p of 0.05 and second branch with C p of 0.0167. Then the branch with C p equal to 0.05 is coupled to stream H 3. That with C p equal to 0.0167 is coupled to H 4. Now, with this coupling the heat duty of both H 3 and H 4 is satisfied. So, those two streams are ticked off and simultaneously the two branches of C 3 are also ticked off. So, that point we know with this coupling both H 3 and H 4 are ticked off, because they have been satisfied and both branches of C 3 are also ticked off. So, we now show those two exchangers on the grid the exchanger we are going to split.

(Refer Slide Time: 47:09)



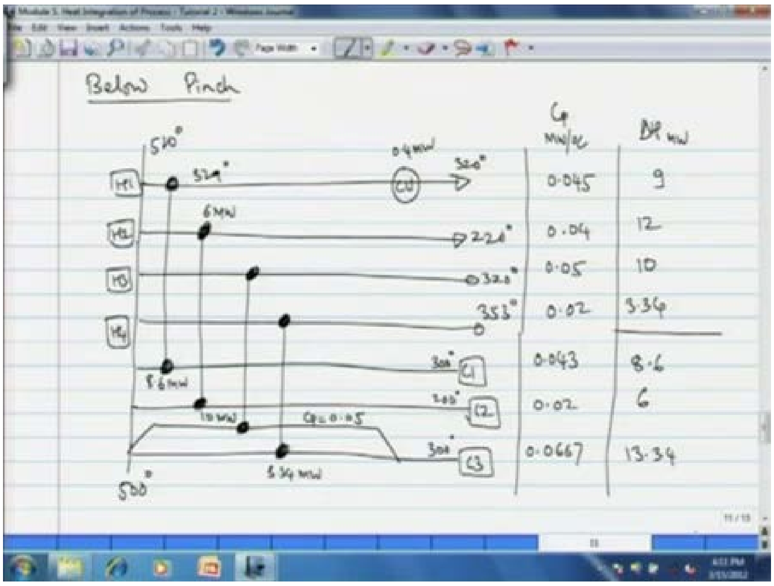
Now, C 3 here we show the split of C 3 upper branch with C p equal to 0.05. Now, this branch is coupled to H 3 and the heat duty on this exchanger is 10 megawatt, the heat requirement of H 3. The second branch is coupled with H 4 and the heat requirement here is 3.34 megawatt, which is the heat duty on H 4. Now, we are left with, now two streams; C 2 and H 2.

(Refer Slide Time: 48:15)



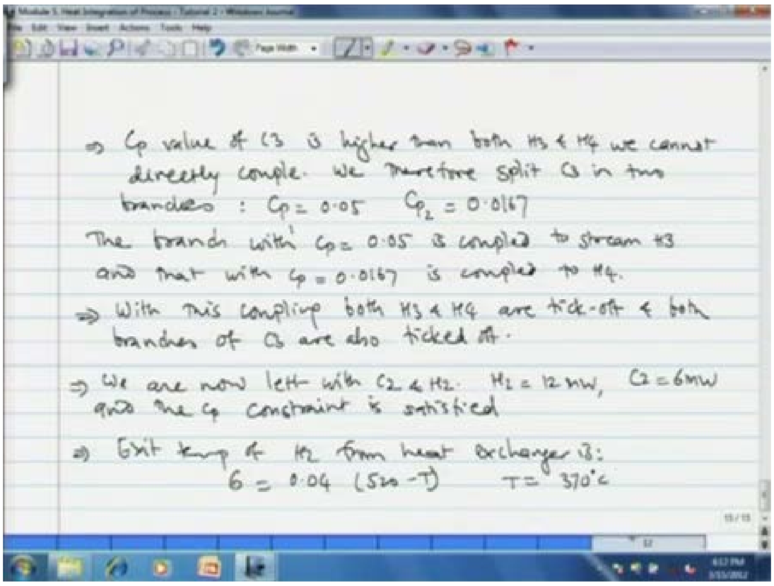
Heat available in H two is 12 megawatt and heat demand on C 2 is 6 megawatt. Moreover, the C p constraint is satisfied you can see that the heat capacity of H 2 is less than, is higher than that of C 2. Now, you can easily couple these two streams H 2 C 2.

(Refer Slide Time: 49:12)



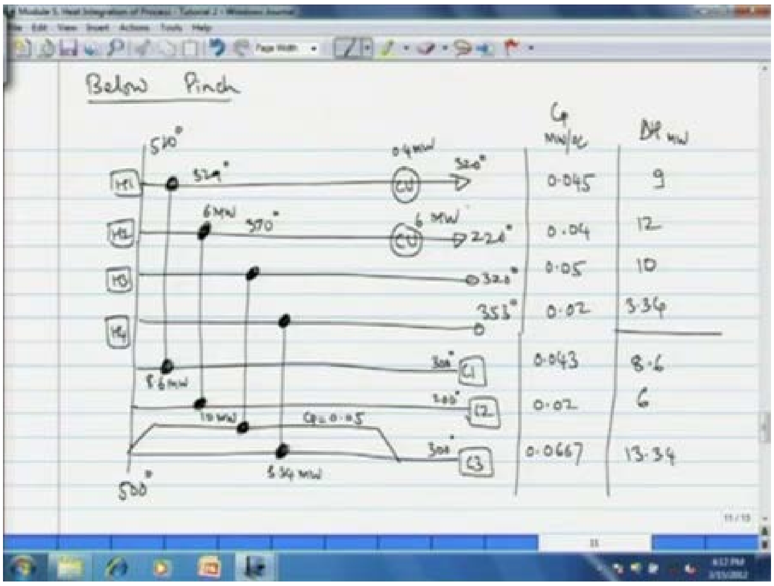
So, now I am placing an exchanger the heat duty on this exchanger, is the heat requirement of C 2; that is 6 megawatt and after emerging from this stream the temperature of H 2 exit.

(Refer Slide Time: 49:44)



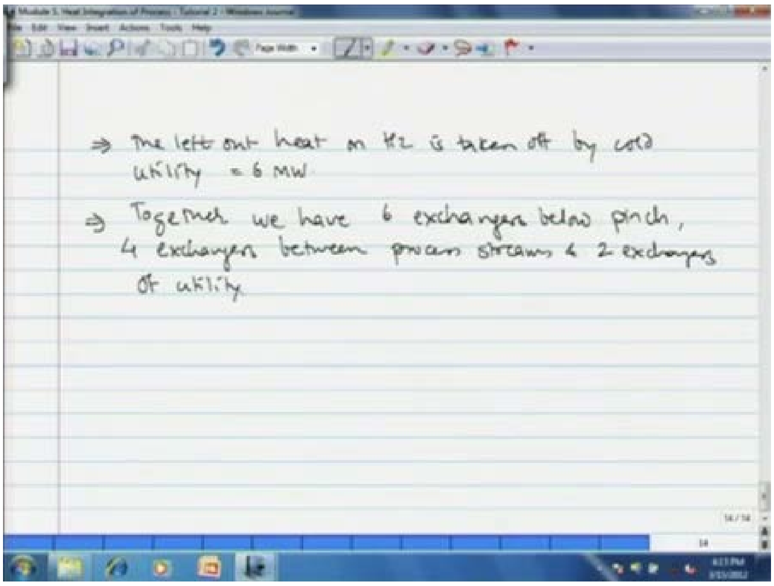
Temperature of H 2 from heat exchanger is 6 megawatt transfer 0.04 into 520 minus T, so heat transfer to be 370 degree centigrade, so that temperature we note here 370 degree centigrade.

(Refer Slide Time: 50:10)



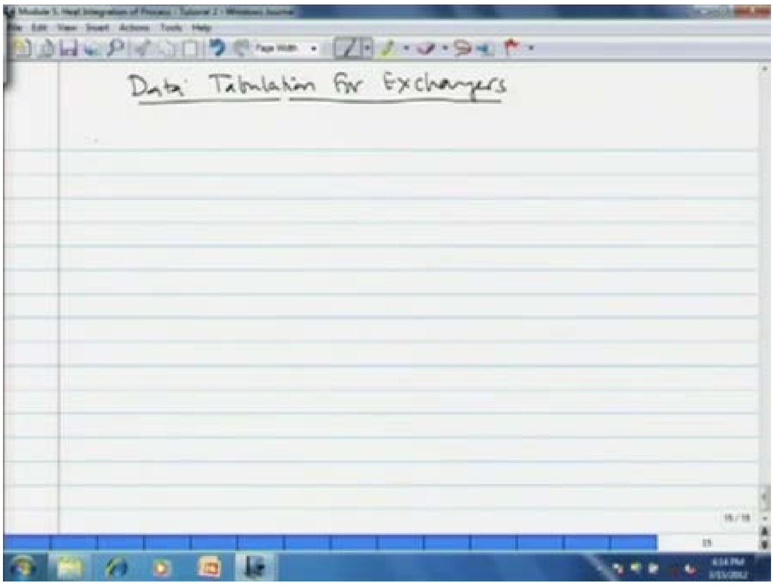
Then we do not have any cold stream left, so the remaining heat of H 2 is then left out to be taken out by the cold utility that is 6 megawatt.

(Refer Slide Time: 50:35)



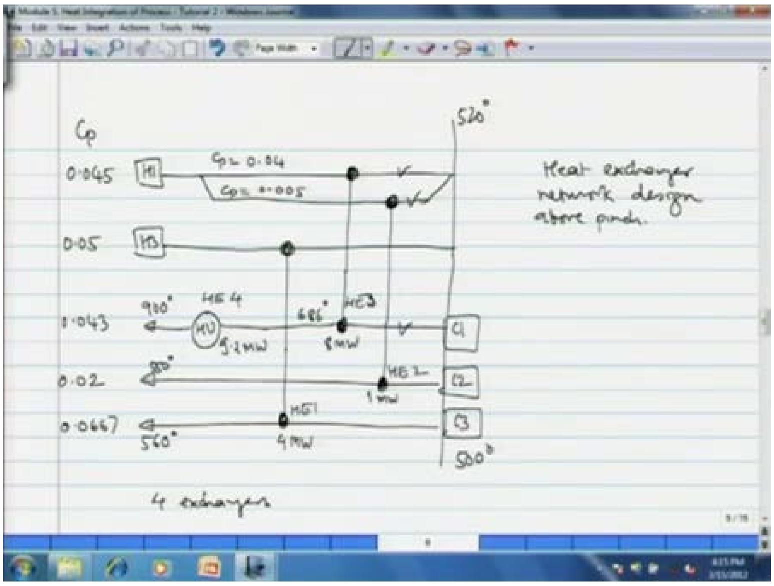
So, together we have 6 exchangers below, pinch 4 exchangers are between process streams and 2 exchangers of utility. So, that completes our heat exchanger network design above and below pinch.

(Refer Slide Time: 51:39)



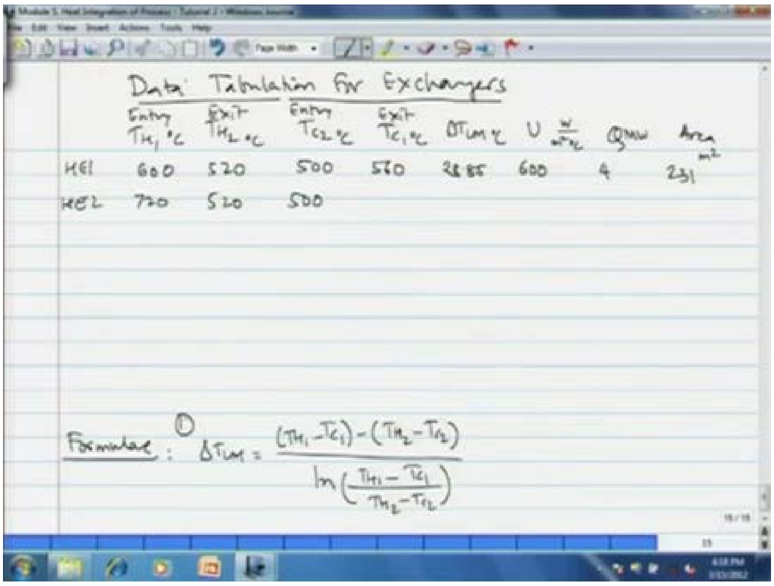
Now, the third bit of the problem is that of determination of data or let us say data tabulation for the exchangers. So, what we have to do now is just pick up the temperatures of the two streams in each exchanger above and below pinch. Then determine the LMTD and thereafter determination of U, overall heat transfer coefficient by simple formula 1 by U is equal to 1 by H i plus 1 by H O. Now, I am giving the exchangers above pinch, we had we had 4 exchangers.

(Refer Slide Time: 52:43)



So, let us call them H U 1, the 4 sorry, the 4 megawatt is 1 H E 1 1 megawatt, H E 2 8 megawatt, H E 3 and 9.2 megawatt. H E 4, now this exercise is pretty straight forward. I am getting you directly the data, you can calculate the, or you can tabulate the data.

(Refer Slide Time: 53:20)

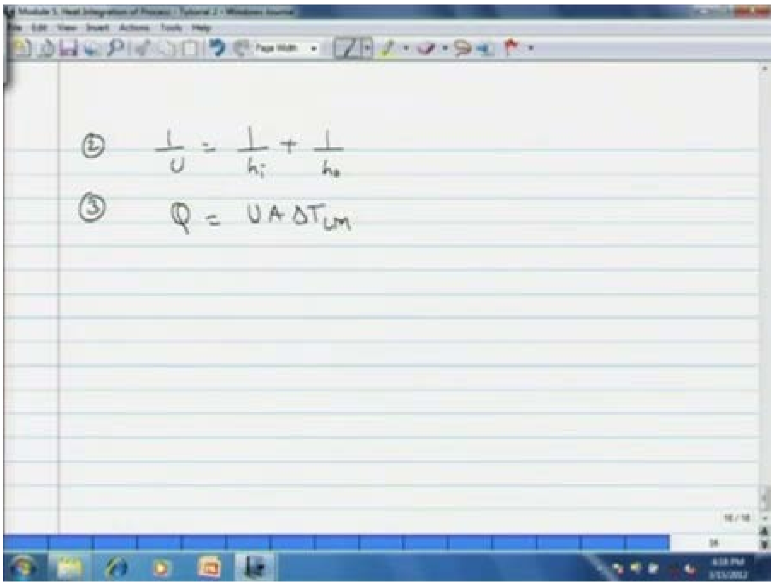


H E 1, the entry temperature of hot stream that we denote by T H 1 600 degrees, exit temperature T H 2, so here I write entry exit for hot stream 520. Similarly, T C 2 is entry for cold stream that is 500 T C 1 is exit for cold stream; that is 560. Then delta T l M is 28.25, sorry 28.85. U is 600 watt per meter square per degree centigrade, we had to…

How did I determine U? I took the film coefficients for the streams C 3 and H 3 like the streams, which are coupled in H 1 and 1 by U is equal to 1 by H i plus 1 by H O. The heat duty on H 1 was 4 megawatt. Then by the simple for formula q is equal to U a delta T the area is determined as 231 meter square. Similarly, for H E 2, I am directly giving the data.

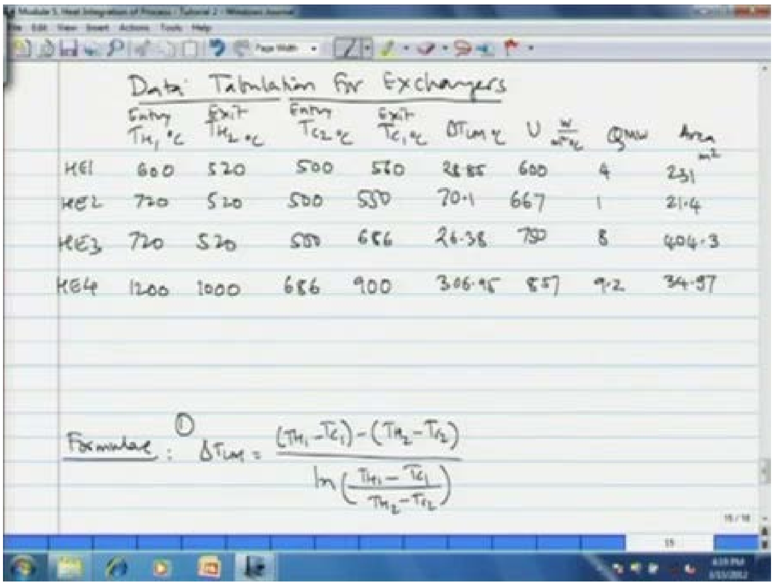
This is pretty easy exercise, I will leave it to you for detailed calculation below. Here I give the formulae, which I have just said formulae delta T l M is equal to T H 1 minus T C 1 minus T H 2 minus T C 2 divided by l M T H 1 minus T C 1 divided by T H 2 minus T C 2. This is the one formula, the second formula is 1 by U is equal to 1 by H i plus 1 by H O.

(Refer Slide Time: 55:50)



The third formula is q is equal to q A delta T l M, using three formulae you can tabulate the data. I am directly giving answers now.

(Refer Slide Time: 56:07)



So, for four exchangers, I am giving answers the exchangers below pinch. I am leaving it as an exercise for you. So, that completes our tutorial on heat exchanger network synthesis using pinch technology. This also completes the module on heat integration of the process.

Thank you.