Process Design Decisions and Project Economics
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Module - 5
Energy (or Heat) Integration of the Process
Lecture -27
Tutorial
Composite Curves, Problem Table Algorithm and Enthalpy Intervals

Welcome, today we will have the first tutorial of module five that is heat integration of the process. We shall see problems on determination of the minimum hot and cold utility requirement plotting of the composite curve, determination of the pinch temperatures and then calculation of the area in a heat integration interval.

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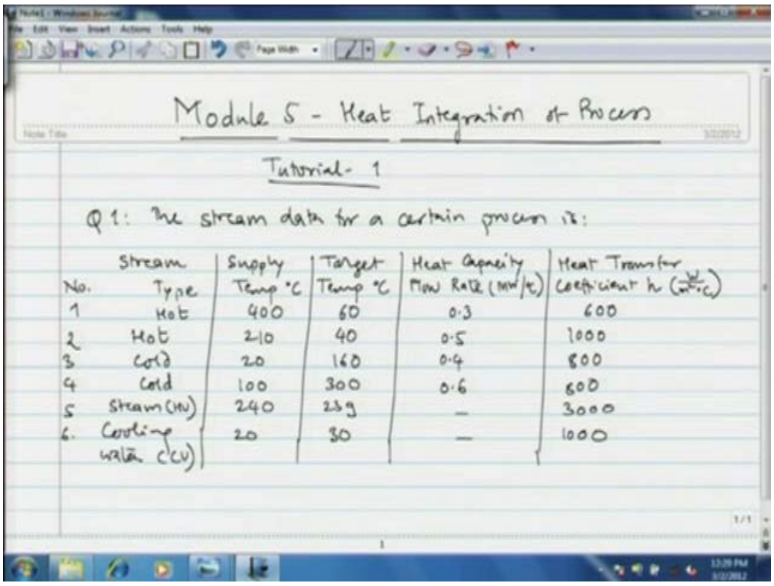

Let me give statement of the first problem that we are going to see today, the stream data for a certain process is as follows, there are two hot streams and two cold streams plus a hot utility and cold utility. So, the stream number and type, then the supply temperature, degree centigrade, the target temperature degree centigrade, the heat capacity flow rate in mega Watt per degree centigrade. Then the heat transfer coefficient in Watt per meter square per degree centigrade, so the data is stream one, it is a hot stream.

The supply temperature is 400 degree centigrade target temperature is 60, the heat capacity flow rate is 0.3 mega Watt per degree centigrade, heat transfer coefficient that we denote by h is 600, second stream is also hot stream. Here, the temp supply temperature is 210, the target temperature is 40 degrees centigrade, heat capacity flow rate 0.5 and heat transfer coefficient of 1000 Watt per meter square per degree centigrade. Then third stream is cold stream the supply temperature is 20 target temperature is 160 heat capacity flow rate point four and heat transfer coefficient 800.

Fourth stream is also cold stream supply temperature 100 target temperature 300 heat capacity flow rate 0.6 and heat transfer coefficient 800, the hot utility is steam hot utility. We denote by h u steam is at temperature of 240 degree centigrade and target temperature is to Pall. We do not take any sub cooling there and the heat transfer coefficient is three thousand Watt per meter square per degree centigrade. Then the cold utility is cooling water it comes at 20 degree centigrade and leaves at 30 degree centigrade and its heat transfer coefficient is thousand Watt per meter square per degree centigrade.

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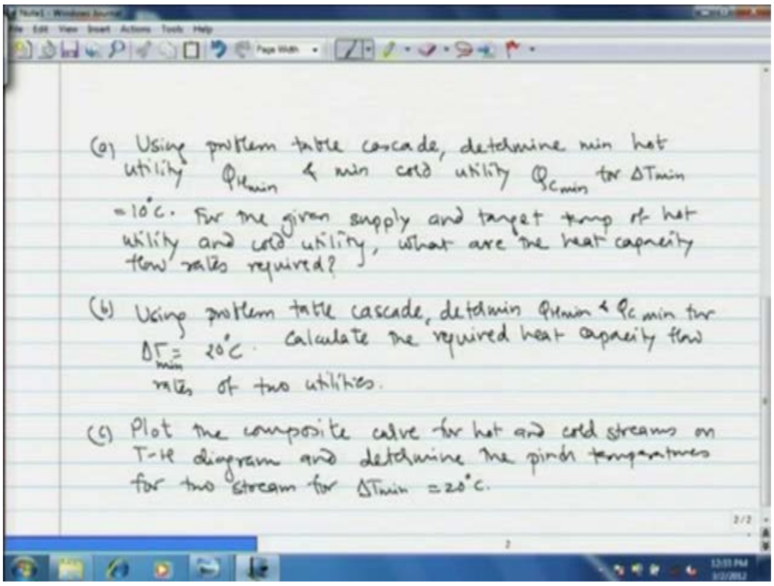

Now, we have to answer three questions based on this stream data, first is that using problem table cascade determine the minimum hot utility hot utility and minimum cold utility minimum hot utility is denoted by acronym Q H min. Minimum cold utility by Q C min and then we are given a delta T min pinch temperature difference of 10 degree centigrade. Now, we have to answer another question here for the given supply and target temperature of hot utility and cold utility what are the heat capacity flow rates that are required. Then the second question that we have to answer is a modified form like here we are given delta T min equal to 20 degree centigrade.

So, same thing using problem table cascade determine Q H min and Q C min for delta T equal to delta T min of 20 degree centigrade and again here we have to calculate the heat capacity flow rates. Calculate the required heat capacity flow rates of the two utilities and the third question that, we have to answer is about plotting the composite curve for hot and cold streams on the temperature enthalpy diagram or T h diagram. Determine the pinch temperatures for the two streams for delta T min of 20 degree centigrade, so let us start the solution.

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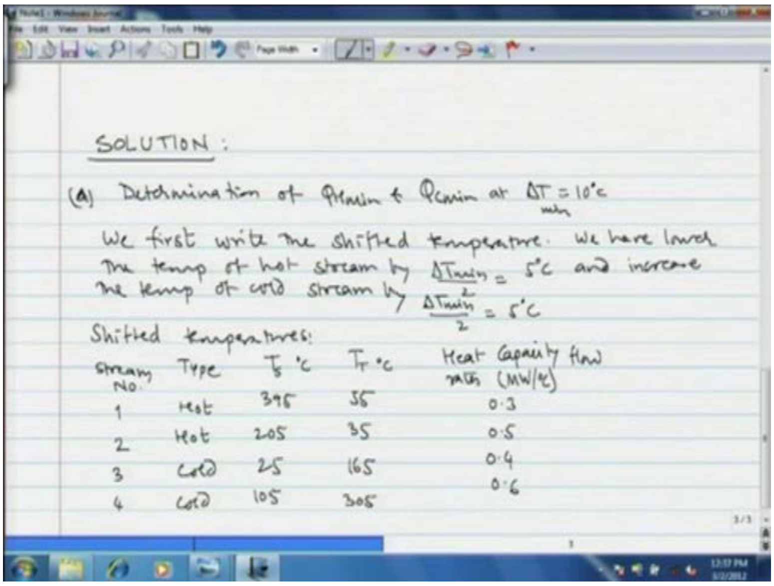

The first question is determination of Q H min and Q C min at delta T equal to 10 degrees centigrade, for this purpose we first shift the temperatures of the streams. We first write the shifted temperatures, we have to shift or lower the temperature of the hot stream by delta T min by 2 or 5 degree centigrade and increase the temperature of cold stream by again same value delta T min by 2 is equal to 5 degrees.

So, the shifted temperatures of the streams are as follows, stream one it is a hot stream supply temperature that we denote by T s degree centigrade is 400 minus 5, so 395. The target temperature is 50 minus 5, sorry 60 minus 5, that is 55, then second stream which is also hot stream. Here, the supply temperature as 200 and 10 that is lowered by 5 degrees to 200 and 5 target temperature was 40 that is again lowered by 5 degrees to 35.

The third stream is a cold stream, here the supply temperature was twenty which is increased by 5 degrees so 25 and target temperature was 160. That is increased by 5 to 165, same the fourth stream is also cold stream here the supply temperature was 100. So, that is shifted to 105 and the target temperature was 300, that is shifted to 305, the heat capacity flow rates, however remain the same I denote. I note down here the heat capacity flow rates for convenience stream 1.3 stream, 2.7 stream 3.4 and stream 4.6, now we have to plot the stream population data.

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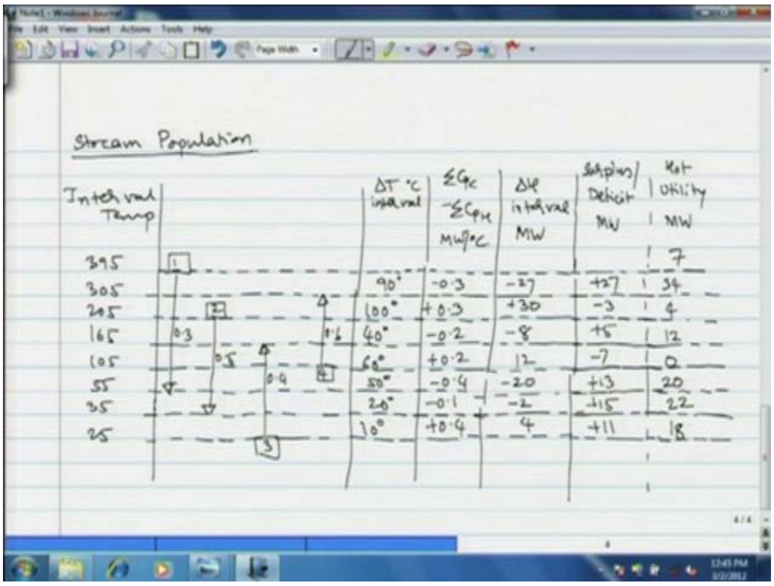

Here, we give the first 30 in interval temperature, we have to identify various intervals of temperature and then mark the streams the highest temperature is 395 there, after 305 there, after 205 there, and after 165, then 105, 55, 35 and 25. Now, delta T interval in degree centigrade the first temperature interval 395 to 305, so 90 degrees then 305 to 205 that is 100 degrees. Then we can write the further intervals, I am giving the values, now directly 10 degrees and now we have to mark the streams in these temperature intervals.

The first stream goes from 395 to 55, it has a c p value of 0.3, so that I write besides the stream then stream two goes from 205 to 35, it has a c p of 0.5. That again we write side at the side the third stream goes from 25 to 165, it has a c p of 0.4 and the fourth stream goes from 105 to 305. It has a c p of 0.6. Now, in each of the temperature interval we have to calculate the sum of the heat capacity flow rates of cold stream minus the sum of heat capacity flow rates of hot streams summation c p c minus summation c p h. This is again mega Watt per degree centigrade, so here in the first interval there is only stream one, so it has a heat capacity of 0.3, but it is hot stream, so minus 0.3 in the second interval, again it is the only stream.

So, there also we have no in the second interval, we have two streams stream one which has a c p of 0.3 and stream four which has a c p of 0.6. So, the summation c p c minus summation c p h is 0.6 minus 0.3, that is 0.3 plus 0.3 and you go further. Now, I am giving values directly in each interval for example, in the interval between 165 to 105, we have all four streams two hot streams and two cold streams summation c p c is 0.4 plus 0.6 that is 1 and summation c p h is 0.3 plus 0.5 that is 0.8. So, 1 minus 0.8 is plus 0.2 and similarly, we can go ahead, I am giving directly values.

Now, we have to calculate the delta h in the interval that is in mega Watt and it can be obtained by multiplication of delta T interval to summation c p c minus summation c p h. So, first interval minus 0.3 in to 90 that is minus 27, then plus 0.3 into 100 that is plus 30, then next is 40 into minus 0.2 is minus 8. Then you can go ahead and now we have to determine whether we have a supply or deficit of the heat in that particular interval negative delta h means there is surplus heat and positive delta h means there is deficit of it, so in the first interval we have excess.

So, it is plus 27 and second interval it is 27 minus 30, so minus 3 then minus 3 minus minus 8, so plus 5, then 5 minus 12 that is minus 7, then minus 7 minus minus 20 that is plus 13. Then 13 minus minus 2, that is plus 15 and 15 minus 4 that is plus 11. Now, here we can see is that the maximum deficit that we have is in the fourth interval, the interval between 100 and 65 and 100 and 5 and that is minus 7.

Now, if we add a hot utility worth that much heat in the first interval, then the net deficit or surplus becomes 0 and that balances the whole streams or the heat balance in the streams enthalpy balance. So, we add 7 mega Watt of hot utility then 7 plus 20, see this 7 add to the 27 available in the second interval, that becomes 34, then out of this 34. We take off 30 the second, so only 4 remain, then to this 4, we add minus 8 of the fourth interval. So, that becomes plus 12 and then 12 minus 12 becomes 0 here, so here we have a pinch and then further the next interval has minus 20.

So, the net utility available or heat available is 20 mega Watt, then out of which again in the next interval you have minus 2. So, that again adds to 22 and to that from this 22, we have to supply 4 mega Watt in the last interval. So, that is we are left with 18 mega Watt, therefore we see that we are left with 18 mega Watt of heat, finally which we have to remove with cold utility.

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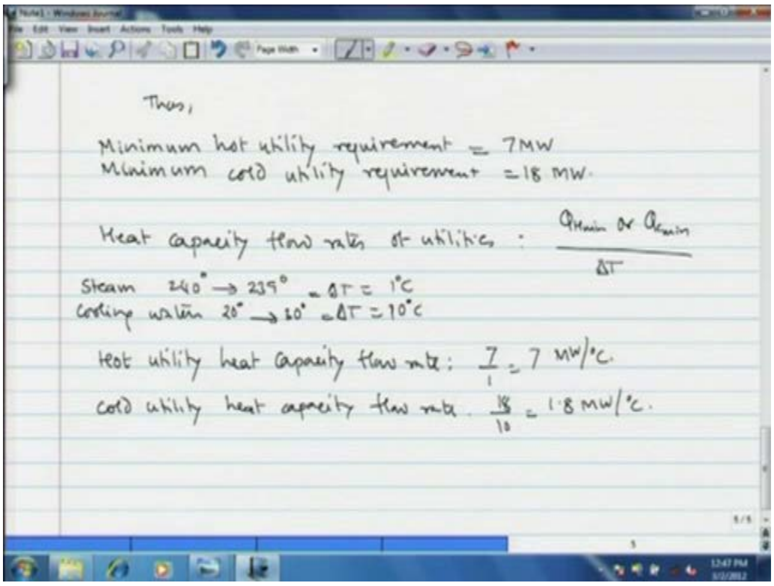

So, the minimum hot utility requirement thus minimum hot utility requirement of the process is 7 mega Watt while the minimum cold utility requirement is 18 mega Watt. So, that is the answer, now we have to also determine the heat capacity flow rates that are required of the two utilities. The heat capacity flow rates is the Q H min or Q C min divided by the temperature interval of that particular utility for steam which is hot utility.

We have supply of 240 and target of 239, so that gives delta T equal to 1 degree centigrade and for cooling water which is cold utility we have supply of 20 degree centigrade target of thirty. So, that gives delta T equal to 10 degree centigrade and therefore the heat capacity flow rate of hot utility is 7 by 1 which is equal to 7 mega Watt per degree centigrade. Cold utility heat capacity flow rate is 18 by 10 that is 1.8 mega Watt per degree centigrade, so that completes the first bit of the problem. Now, in the second bit we have to repeat the same thing for delta T min equal to 20 degree centigrade.

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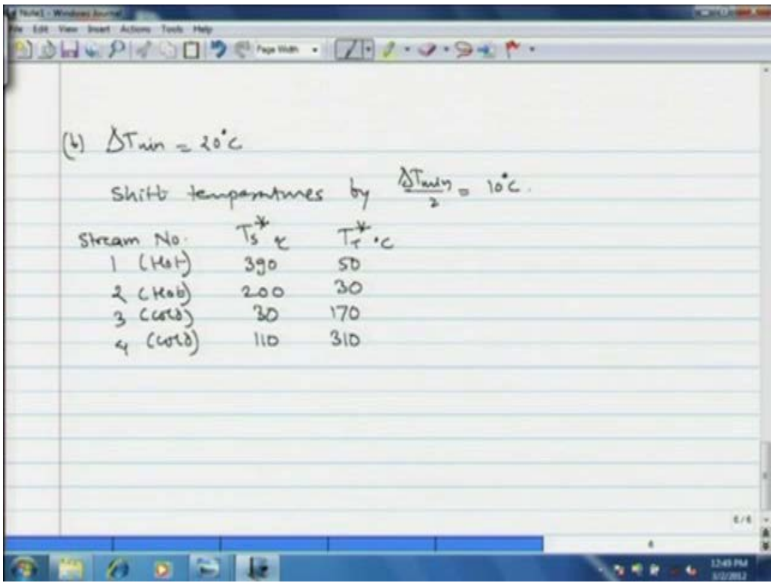

Now, here I will leave most of the things to you because it is rather straight forward exercise with delta T min equal to 20 degree centigrade. I will give only the answers here we have to shift temperatures by delta T min by 2 that is 10 degree centigrade. So, the sub plant target shifted temperature interval becomes steam one shifted temperature that we denote by T s star and T T shifted temperature interval by T T star. So, supply was at 350, so that becomes 340, oh the sorry the supply was at 400, so that becomes 390, then target was 60, so that becomes 50, 15 by 10 degrees, then similarly for other streams we can write the temperatures, now next is the stream population data.

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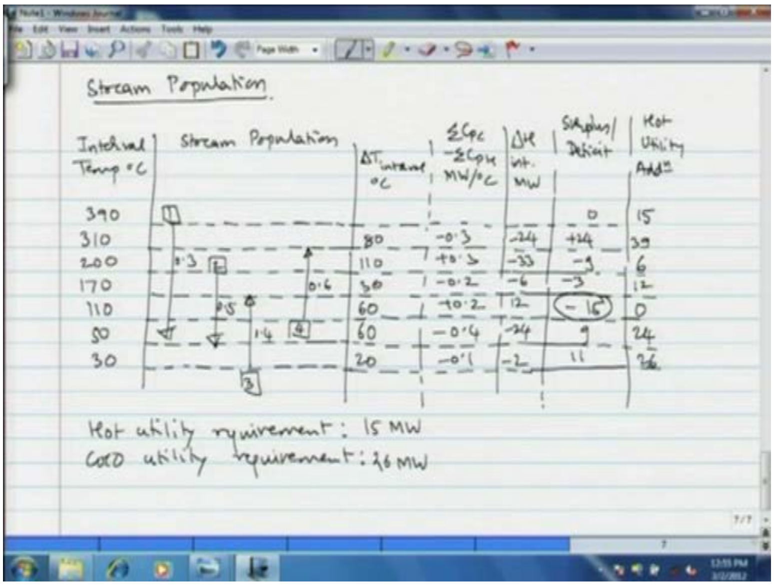

Here, we have interval temperature, we have now highest temperature 390, then 300 and 10, 200, 170, 110, 50 and 30 and then the stream population first stream goes from three 90 to 50 with c p of 0.3. The second stream goes from 200 to 50, the third stream goes from 30 degrees to 170 and the fourth stream goes from 110 to 310, the c p values we write besides the stream 0.5 for 2.4 for 3.6 for 4.

Now, delta T interval degree centigrade is 80 is 100 and 10, then 30, 60, 60 and 20, then next is summation c p c minus summation c p h. Here, again this remains same as previous minus 0.3 plus 0.3 minus 0.2 plus 0.2 minus 0.4 and minus 0.1. Then we have to calculate the delta h in the interval minus 24 minus 33 minus 6 12 minus 24 minus two and then surplus deficit of heat.

So, in the first interval we have plus 24, then minus 933 taken off then minus 3 minus 15 9 and 11 and thus we see here is that the minus maximum negative maximum deficit is in the fifth interval of minus 15 mega Watt. So, that much hot utility we have to add to the first interval so 15 then 30 nine after hot utility addition the cumulative delta h in each interval is 15 mega Watt in the first then 15 plus 15 minus minus 24. So, 39, then 39 minus 33 that is 6 6 minus minus 6 12 then here it becomes 0 12 minus 12 and then 9.

This is minus 24, so plus 24 and 24 minus minus 2 that is 26, so here we need a hot utility require hot utility requirement. For this is 15 mega Watt and then after supplying, supplying of 15 mega Watt, we are left with 26 mega Watt of surplus heat, which we have to discard to cold utility. So, cold utility requirement is 26 mega Watt, now the heat capacity flow rates are for hot utility 15 Mega Watt divided by 1 degrees so 15 mega Watt per degree centigrade and for cold utility it is 26 mega Watt by 10 degrees. So, 2.6 mega Watt per degree centigrade, so that completes the second problem.

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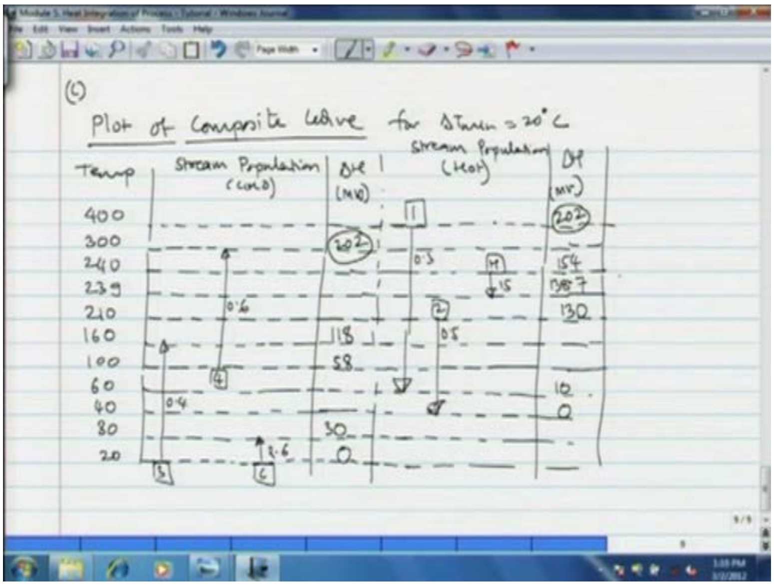

Now, in the third bit we have to plot the composite curve here we have to calculate the cumulative enthalpy of different streams. Now, we have total three hot streams and three cold streams out of which two are process and one is one is utility each. Now, here we give the direct temperature interval the highest temperature is 400, 300 thereafter 240,239 of steam there after 200 and 10, 160, 100, 60, 40, 30 and 20.

Now, again we have to give the stream data here, the three hot streams are let us say first we start the cold streams stream population. The third cold stream goes from 20 degrees, let us see the third bit of the problem plot of composite curve for delta T min equal to 10 degree centigrade. Now, here we have to calculate sorry delta T min of 20 degree centigrade not 10 degree centigrade delta T min of 20 degree centigrade. So, here what we do is that first we calculate the cumulative enthalpy of the hot streams and the cold stream that is a composite curve. So, here again we make a temperature a stream population diagram the highest temperature is 400, then 300, then 243 239. So, we basically list all the temperatures in the process in the decreasing order and then we plot the streams in that particular temperature interval.

So, let us start with the cold streams first stream three goes from 20 degrees from 160 degrees and it has a c p of 0.4, then stream four goes from 100 degrees to 300 degrees and it has a c p of 0.6 and the cold utility goes from 20 degrees to 30 degrees. As we just calculated it has a c p of 2.6 mega Watt, now let us calculate the delta h of the composite stream, we assume here that the cold the least temperature of the cold stream is 20 degrees.

So, that we take as a reference temperature and then we assume the delta h enthalpy of the composite curve to be 0 at that reference temperature. Now, as long as the number of streams in a particular temperature interval or succeeding temperature interval remains constant, we will have a straight line of the composite curve whenever there is addition or deletion of any stream. Then the slope of that particular curve will change, now let us see the first interval we assume for cold streams enthalpy to be 0 at 20 degree centigrade. So, between 20 and 30 we have two streams the third stream and cold utility and together they have a heat capacity of 2.6 plus 0.4, that is 2 mega hertz per degree centigrade and temperature interval is 10 degrees.

So, at 30 degrees we have the net total enthalpy composite enthalpy of cold streams as thirty mega Watt. Now between 30 and 60 we say that there is only one stream that is the third stream with 0.4 heat capacity. Then at 100 degree centigrade we again calculate because between 30 and 100 there is only one stream so we will not have any change of slope. Therefore, from 30 to 100 that is 70 plus 70 in to 0.4, that is 28 and plus 30, that is 58. So, at 100 degree centigrade, the total enthalpy of the cold composite curve will be 58 mega Watt from 100 degree centigrade stream four adds.

Till 160, we have two streams number 3 and 4, so again we have to calculate the enthalpy at 160 in centigrade the temperature interval from 100 to 160 degrees and the total c p is 0.4 plus 0.6 that is 1, so 258, we add 60 in to 1 that is 180. Then from 160 on words we have only one stream that is the number four stream and then it goes up to 300 degree centigrade with a temperature interval of 140 and it has a c cp of 0.6. So, that again adds 84 mega Watt and then the total becomes here at 300 degree centigrade, 202 mega Watt.

So, that is the enthalpy temperature data for the cold composite curve, similarly for hot composite curve first of all we have to give the stream population I am extending the temperature interval lines. Now, we have the first hot stream number one stream going from temperature 100 degree four hundred degrees 400 degrees to 60 degrees. Then, we have number two stream going from 210 to 40 degrees then hot hot utility from 240 to 239, number one stream has c p of 0.3 number two stream has c p of 0.5 and hot hot utility has a c p of 15. Now, we have to calculate delta h for the hot composite stream here the least temperature is 40 degrees, so we take 40 degree as a reference temperature and assume 0 enthalpy here. Then again do the same way as we did before that we check where till what temperature range the stream population is remaining constant.

So, till that point the composite curve will have same slope, so here we see that for temperature intervals 40 to 60, there is only one stream that is number 260 on words the number one stream adds. So, at 60 degrees the n the total cumulative on the enthalpy is 0.5 in to 20 that is 10, then till 200 and 10 temperatures. There are two streams number one and number two and together they have a c p of 0.8.

So, we add from 60 to 200 and 10, so 150 degrees interval in to 0.8, so 120 mega Watt, so the total cumulative enthalpy at 210 degrees is 130, then between 210 and 239, there are two streams number one and number two. So, the cumulative enthalpy at 239 is 138.7, so 0.3 plus 0.5 into 29, so that is what we have added and finally we have at 240 degrees the hot utility. So, up to 240 there are two streams again hot utility 15 mega Watt per degree centigrade number one stream with 0.3.

So, 15.3 in to 1 so that is 15.3 that we add, so this becomes 154 cumulative enthalpy and in the last interval from 240 to 240, sorry 240 to 400, we have only one stream number one stream with c p of 0.3. So, that is 160 in to 0.3, so that we get another 48 mega Watt to that that cumulative becomes 202. So, then we can see here that this is the completely balanced curve the total cumulative enthalpy of cold stream and total cumulative enthalpy of hot streams is exactly the same. Now, we have to plot the temperature versus H data cumulative h data for hot composite stream and cold composite stream.

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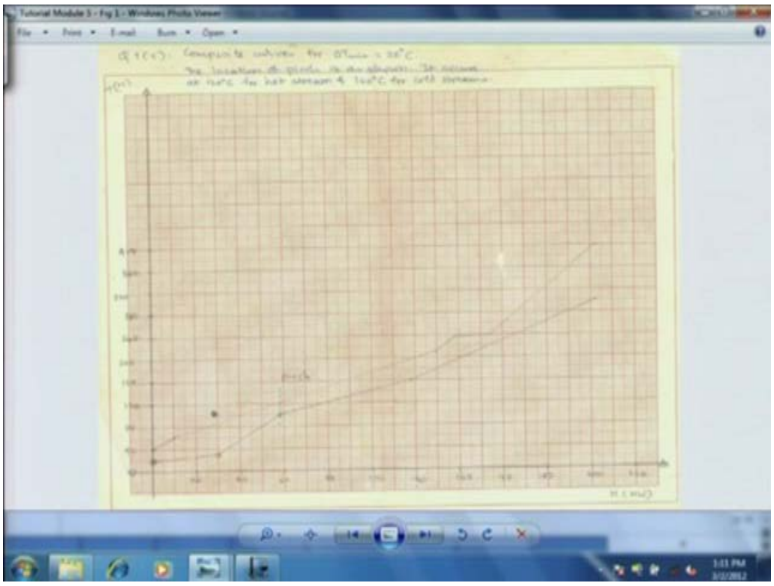

That graph I am showing you, now what you see on the screen is a composite curve for delta T min equal to 20 degree centigrade and then we have to find out the pinch. Here, we can see that the pinch occurs at 120 degree centigrade for the hot stream and 110 degree centigrade, sorry 100 degree centigrade for the cold composite stream. So, here you have one pinch there is another pinch also seen here at 240 and 220, so here we have basically two pinches each one pinch is at 120 and 100 and another pinch is at 240 and 220 so that point we note.

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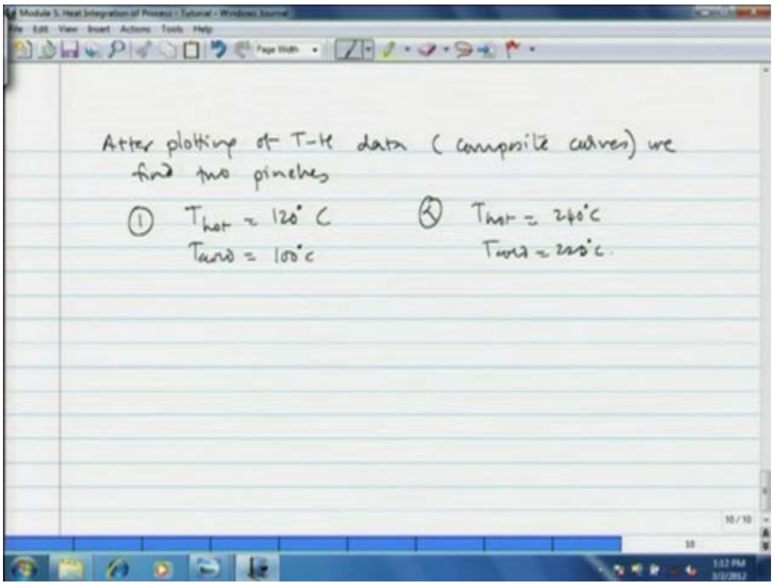

Here, after plotting of the after plotting of H, T H data that is composite curves, we find two pinches one pinch at T hot 120 and T cold 100 degree centigrade. Second pinch at T hot in to 240 degree centigrade and T cold as 220 degree centigrade, so that completes the third bit of the problem.

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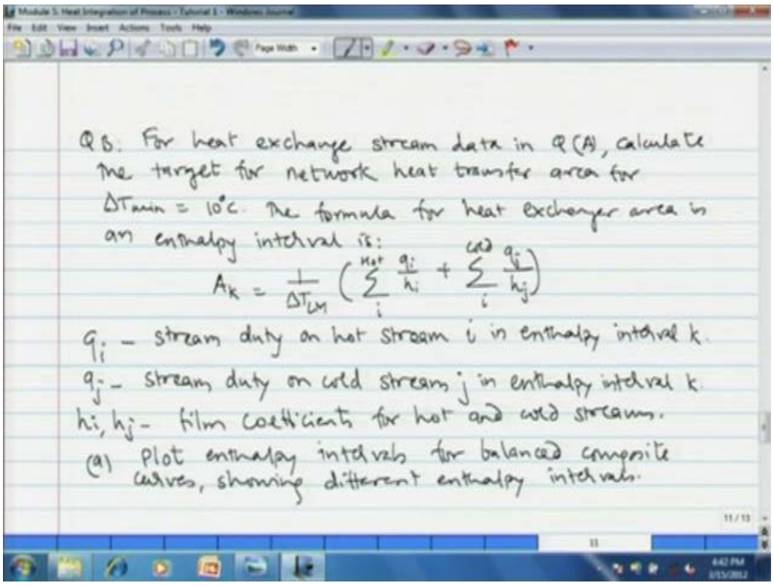

The next question is on enthalpy intervals the problem statement appears on your screen for heat extends stream data same as a previous question calculate the target for network heat transfer area for delta T minimum equal to 10 degree centigrade. We have earlier done calculation for determination of Q H min and Q C min for delta T min equal to 10 degree centigrade. So, we make use of that answer for this question we have been given a formula for heat exchanger area in an enthalpy interval enthalpy interval k the area in it a k is 1 by delta T l m in to the bracket summation q i by h i for all hot streams plus for summation q a by h a for all cold streams.

The notations are given q i is the stream duty on hot stream i in an enthalpy interval k q a is the stream duty on cold stream j in enthalpy interval k h i and h j are film coefficients for hot and cold streams. We have two answers here again coefficients first plot the enthalpy interval intervals for balance composite curve showing the different enthalpy intervals for delta T min equal to 10 degree centigrade.

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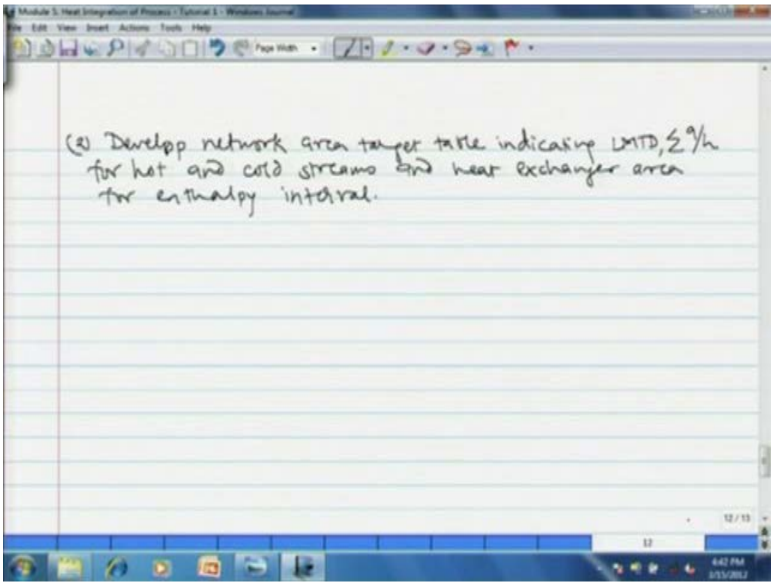

Secondly, we have to develop the network area target table indicating l m T d summation q by h for hot and cold streams and the heat exchanger area for the enthalpy intervals.

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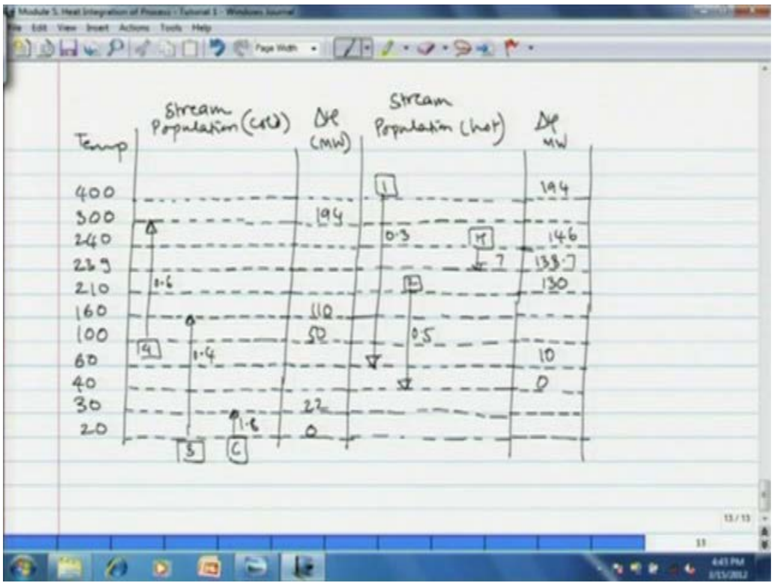

We start with the first bit that is plotting of the composite curves and identification of the enthalpy intervals now what you see on the screen is the enthalpy interval data. We have listed all the temperatures in the process in descending order then we have also listed the stream population like stream we have two hot streams three and four.

Number three stream goes from 20 degrees to 160 degrees with c p value of 0.4 and then number four stream goes from 100 to 300 with c p value of 0.6 for cold streams. The minimum temperature is 20 degree, so we take that as basis for calculation of composite enthalpy. So, zero enthalpy at 20 degree centigrade and then at interval 20 to 30, we have two streams three and cold streams and a total enthalpy at thirty degrees is 22 between 22 and 100 we have only one stream that is stream three.

Then, the enthalpy at 100 degree centigrade is 50 between 100 and 160, we have two streams three and four and enthalpy at 160 is 100 and 10 and from 160 to 300. We have only stream four and the total enthalpy at 300 degree centigrade is 194. Similarly, we go for hot streams we have two hot streams one and two and one hot utility and the minimum temperature for hot streams is 40 degree centigrade. So, we take that as basis zero enthalpy at 40 degree centigrade and then we list the enthalpies for different In intervals.

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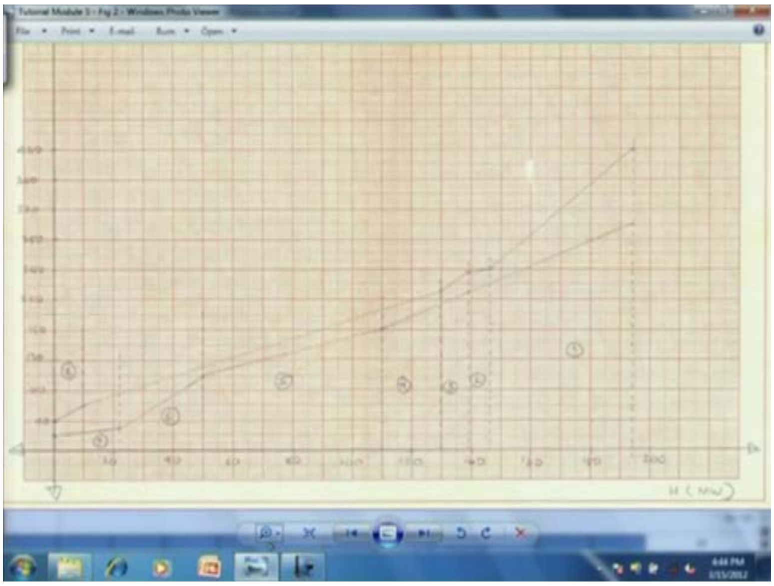

When we plot this temperature versus enthalpy we get the T h diagram or composite enthalpy interval diagram composite curve diagram. Now, what you see is identification of different enthalpy intervals like the first interval is here be between four hundred for hot composite stream to 240 then 240 to 239. Whenever, the composite curve changes its low either hot or cold that is one enthalpy interval, so together we have one, two, three, four, five.

The longest interval six, seven and eight enthalpy intervals 8 times, either the hot composite stream or cold composite stream changes. It is low that means the number of streams in that interval changes either one stream adds or a one gets deleted. Therefore, the slope changes, so we have identified total eight enthalpy intervals we shall list these now by particular lines.

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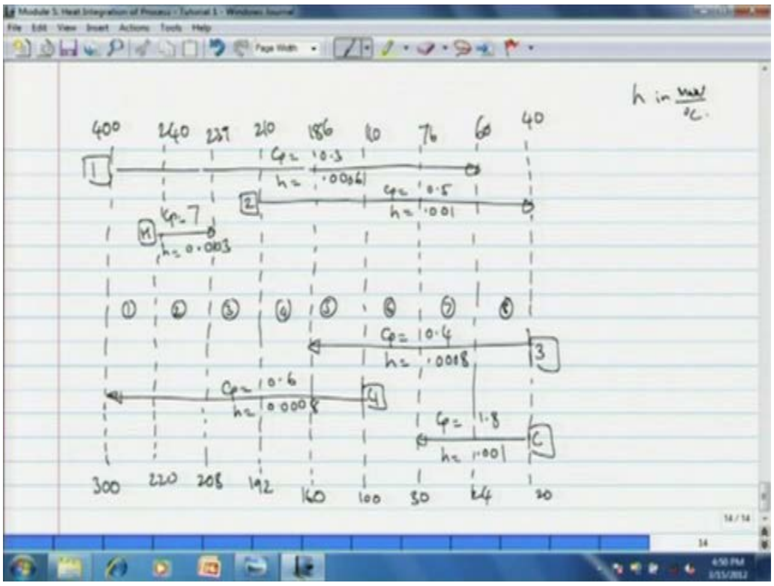

The first interval Four hundred for hot composite stream 300 for cold composite stream then 240 for hot 220 corresponding temperature for cold, then 239, this is at 240 to 239 is a interval where hot utility adds. So, above 240 hot utility is not there below two thirty nine also it is not there so the corresponding temperature is 208, 210. Here, we can see this 210, this temperature this interval we are add and the corresponding cold composite temperature is 192, then 186, 160, 100.

Then, 100 this is a pinch 76 and corresponding temperature is 30, then 60 corresponding temperature is 24 and 40 and corresponding temperature is 20 in this enthalpy intervals. We shall list all the streams like stream one is in all the intervals, but the last. So, enthalpy interval one two, three, four, five, six, seven and eight, so number one stream is in interval one to seven similarly, number two streams number two stream is from four to eight.

I will also write above it its db value and the value of h the film coefficient h is being written in mega Watt per degree centigrade. Hot utility is between two forty two to two thirty nine c p value of 7 h of 0.003 then the cold number three stream goes from it to fifth interval c p value 0.4, h 0.00088, 100 Watt per meter per degree centigrade. Then number fourth stream goes to from four hundred to three hundred here c p is 0.6 h is 800 Watt per meter square per degree centigrade or or a 0.008 mega Watt. Then cold u utility goes from 20 to 30 degrees here c p value is 1.8 we have already determined it in the previous example and h value is 0.001 or 1000 Watt per meter square per degree centigrade.

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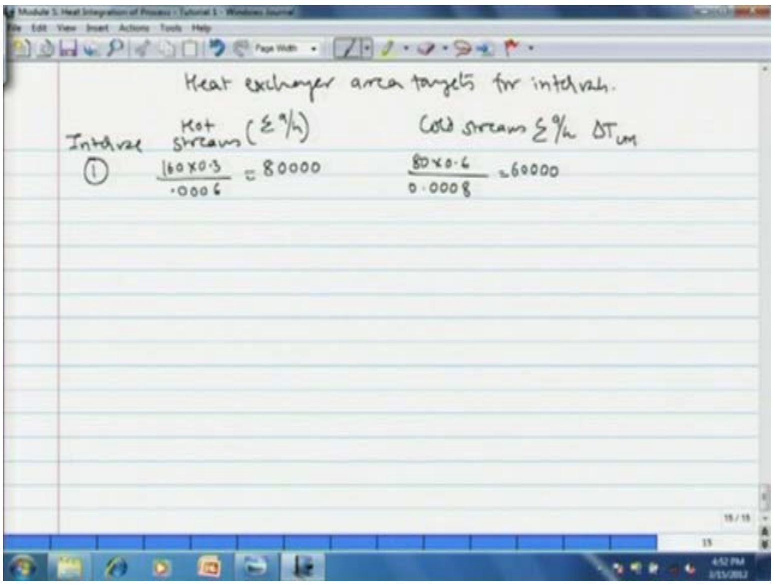

Now, with this stream population data enthalpy interval data we have to tabulate the network target heat exchanger area targets or targets for interval. Now, let us take interval one interval one has only one hot stream as you see here the temperature difference is 400 to 240 so 160. Heat duty is 160 in to 0.3 the heat capacity divided, now we have calculating summation q by h so q is 160 in to point three h is 0.0006, so that serve to be 80 cold streams cold streams. We have in the first interval only the fourth stream number four stream it goes from 220 to 300, so 80 degree is difference c p value of 0.6 so that we note here 80 in to 0.6 and its h is 800 Watt meter square per degree centigrade or 0.008. So, this is 60000 summation q by h and then delta T l m delta T l m.

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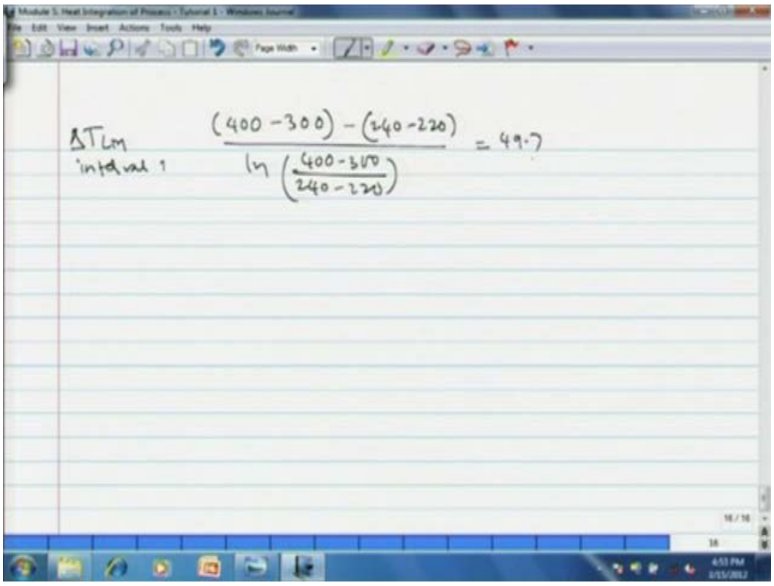

For interval one we have 400 degrees centigrade entry temperature for hot composite and three hundred degrees exit temperature for cold composite. So, delta T at one end or left end is 400 minus 300. Similarly, we have 240 and 220, 240 exit temperature of hot stream 20 temperature of cold stream, so 240 minus 220 divided by l n of 400 minus 300 divided by 240 minus 220. So, this transfers to be 49.7, so that point we note here.

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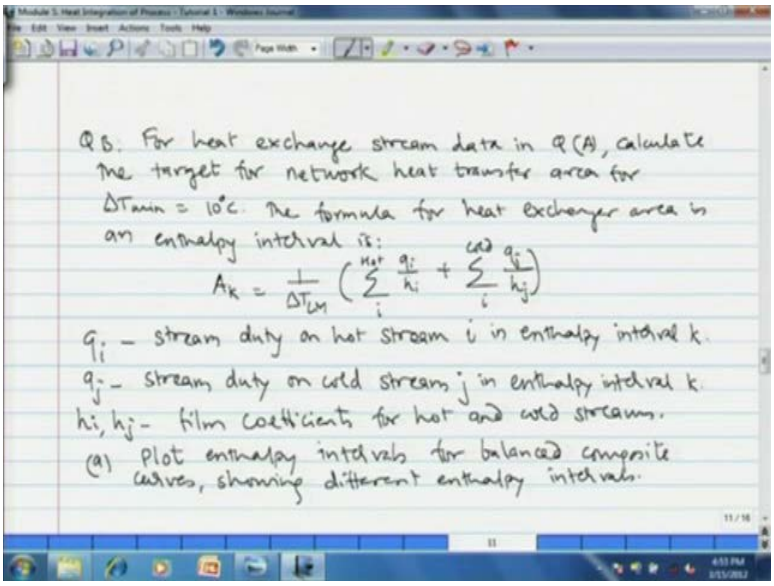

Then, using the formula then what we are given a is equal to 1 by delta T m n summation q by h hot plus summation q by h cold we get area.

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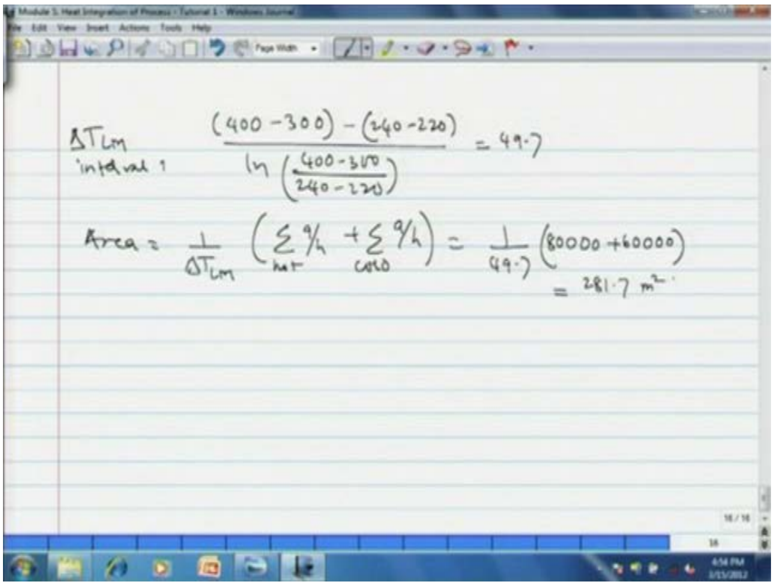

So, that I will show you the exact calculation area is 1 by delta T l m summation q by h hot plus summation q by h cold. We have all the values delta T l m 42.7 majors determinate plus 80,000 plus 60,000 summation q by h for hot and cold and area thus turns out to be 281.7 meters square.

In interval twelve thousand delta T l m 23.91 area 1108.3 number four we have two streams here number one and number two stream the temperature difference is 24. So, summation q by h and this is total 12,000 each cold streams available is only number four temperature difference is 32 degrees h value is 800 Watt per meter square per degree centigrade. So, this is 24,000 q by h summation q by h delta T l m is 21.76 and area is 2205.8. Similarly, you can carry out the other intervals the total area, I leave it as an exercise, so this completes the first tutorial of the module of integration of the process. In the next tutorial, we shall see the design of heat exchanger network that is coupling between the streams using the pinch technology.

Thank you.