Refrigeration and Air Conditioning
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Lecture No. # 32
Analysis of Complete Vapour Compression System

Welcome back in the last few lectures. We discussed the performance aspects of individual components of a vapor compression refrigerant system.

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In this lecture, I shall discuss the analysis of the complete vapor compression refrigerant system. So the specific objectives of this particular lecture are to introduce the concept of complete system analysis, discuss briefly the graphical and mathematical methods illustrate the concept with a simple example and finally discuss briefly the importance of sensitivity analysis.

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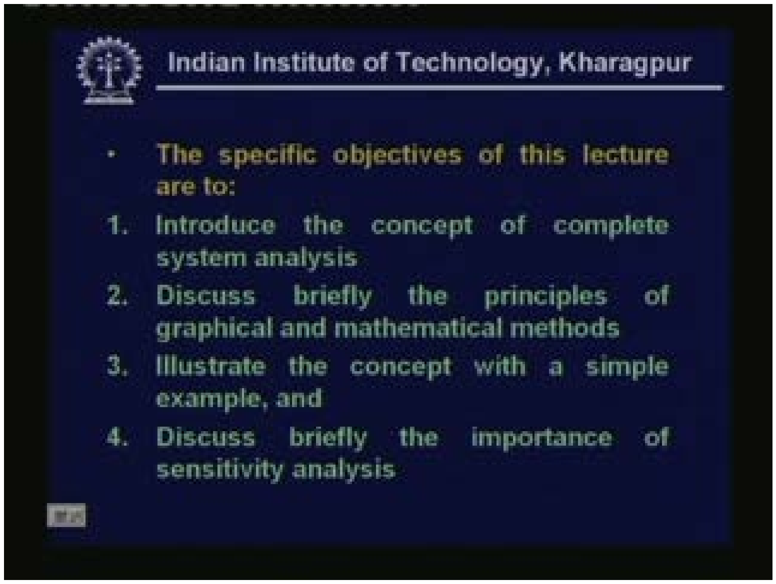

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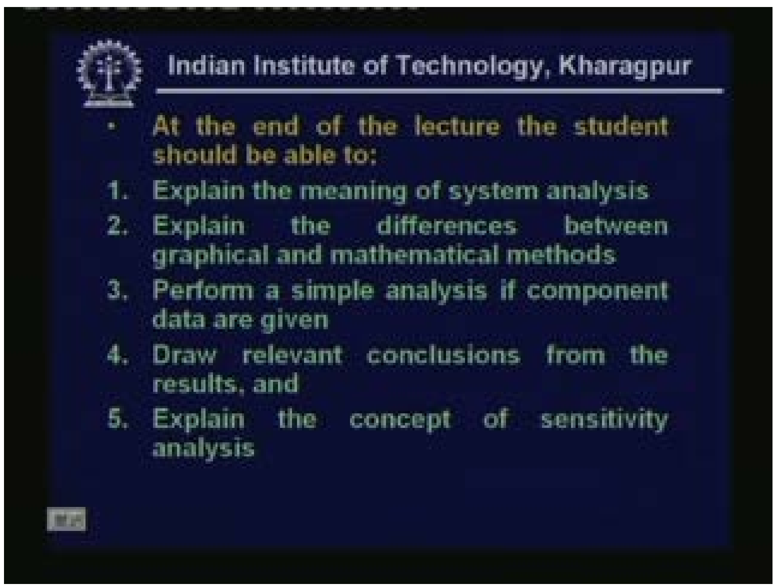

At the end of the lecture you should be able to explain the meaning of system analysis, explain the difference between graphical and mathematical methods, perform a simple analysis if component data are given, draw relevant conclusion from the results and finally explain the concept of sensitivity analysis.

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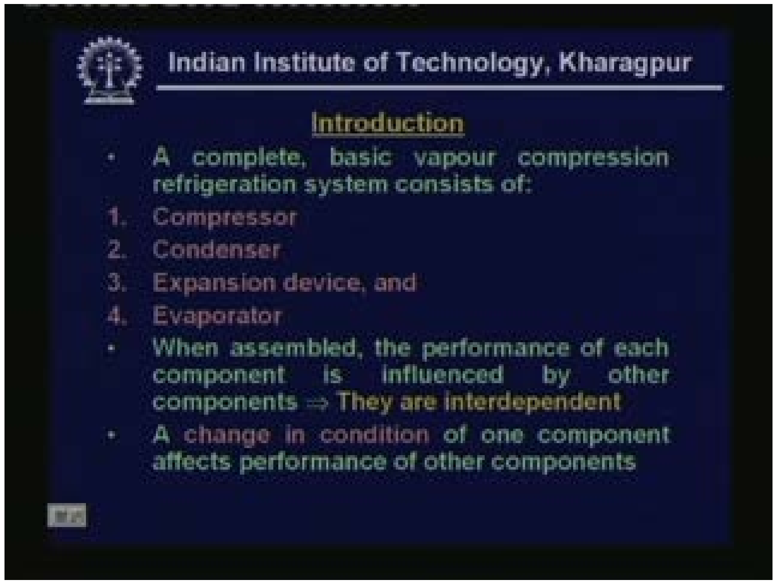

Let me give a brief introduction. A complete basic vapor compression refrigeration system consist of as you know a compressor, a condenser expansion device and the evaporator. When assembled the performance of each component is influenced by other components. That means they are interdependent when they are assembled in a system 1. A change in condition of one component affects performance of other components.

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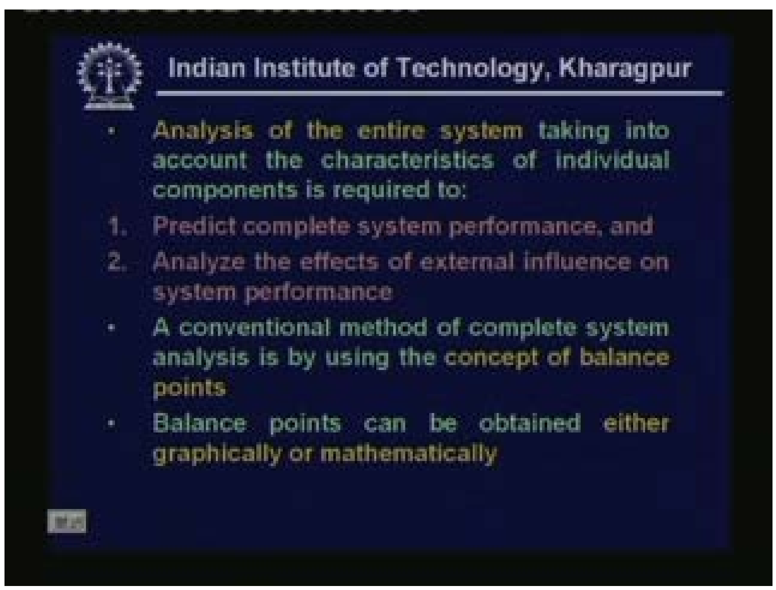

Analysis of the entire system taking into account the characteristics of individual components is very much required to predict complete system performance. And analyze the effects of external influence on system performance a conventional method of complete system analysis is by using the concept of balance points balance points can be obtained graphically or mathematically.

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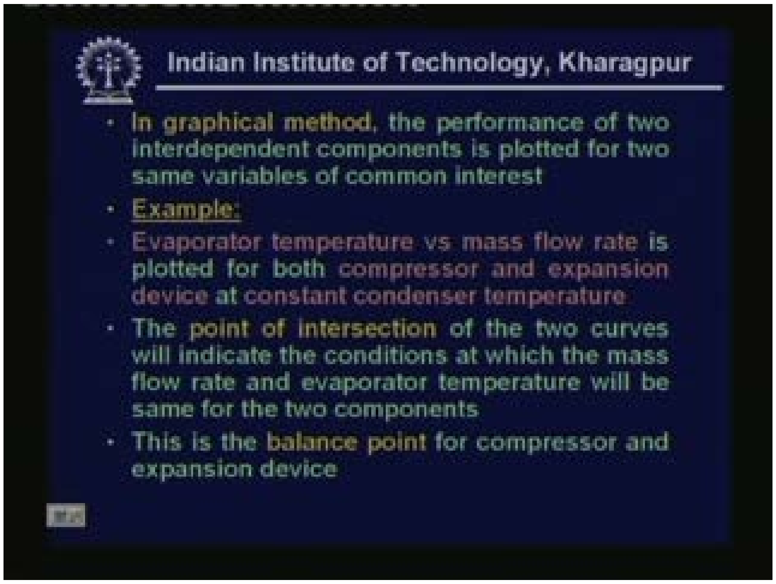

In graphical method the performance of two interdependent components is plotted for two same variables of common interest. Let me give an example in fact we have used this while discussing expansion devices I am going to give same example the evaporator temperature versed mass flow rate is plotted for both compressor and expansion device. At constant condenser temperature the point of intersection of two curves will indicate the conditions at which the mass flow rate and the evaporator temperature will be same for the two components. This is the balance point for compressor and expansion device. So basically the graphical method we have discussed while discussing the performance accepts of as I said expansion devices. What we have done there is we have plotted the mass flow rate of compressor and mass flows are of capillary tube verses the evaporated temperature.

So we got two curves one for compressor and one for the capillary tube and the point where these two curves intersects is the point where the mass flow rate through the compressor is equal to the mass flow rate through the capillary tube. We call that point as the balance point okay because at that point the system is balanced and the corresponding evaporator temperature is called as the evaporator temperature at the balance point okay. So we have use this graphical method in case of compressor and capillary. Now the same method can be extended to other components also for example condenser and compressor condenser and capillary and the evaporator etcetera. Okay this kind of analysis is known as graphical method of analyzing the system.

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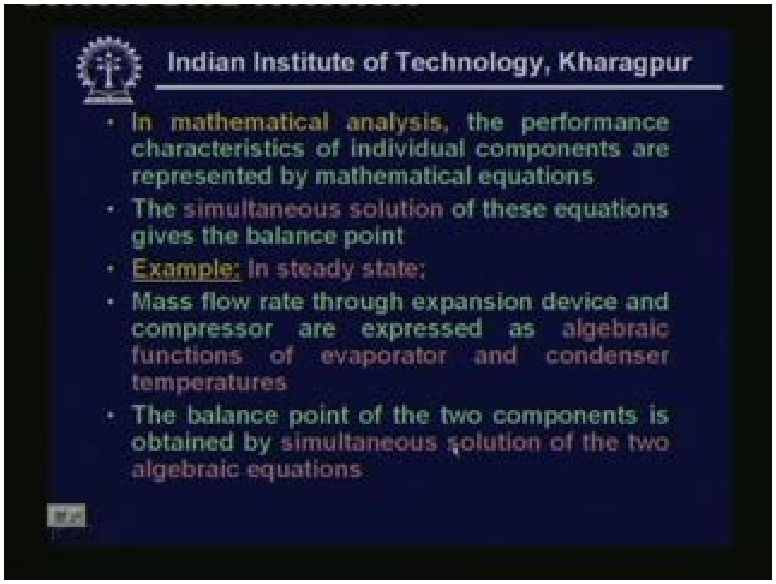

Now in mathematical analysis the performance characteristics of individual components are represented by mathematical equations. So as the name implies you have equations for individual components and the simultaneous solution of these equations gives the balance point. For example in steady state mass flow rate through expansion device and compressor are expressed as algebraic functions of evaporator and condenser temperatures. The balance point of the two components is obtained by simultaneous solution of the two algebraic equations. That means we had for example at a fixed condenser temperature we have one curve for the mass flow rate of compressor as the function of the evaporator temperature if you vary the condenser temperature you get another curve okay.

Likewise you can generate several curves for different condenser temperatures. Similarly you can also generate the mass flow rate curves for capillary tube at different condenser temperature and as a function of evaporator temperatures. So we can do the curve fitting for these curves okay, by using analysis and we can get finally express the mass flow rate of the compressor. And the mass flow rate of the capillary as a algebraic function of evaporator and the condenser temperature. So in order to find the balance point what we have to do is have to simultaneously solve these two algebraic equations okay. So at balance point as you know the mass flow rate through the compressor is equal to the mass flow rate though the capillary. So that is the condition we have to apply to these two equation and we have to find out the value of evaporator and condenser temperature at which this balance takes place. So that is the balance point and this is the method of mathematical analysis okay.

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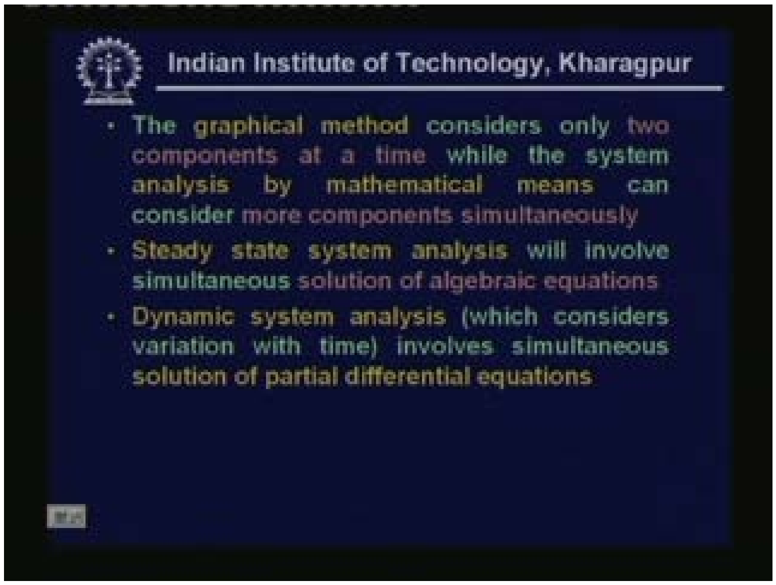

So the graphical method considers only two components at a time for example compressor and capillary okay. While the system analysis by mathematical means can consider more components simultaneously okay. This is the major difference between graphical method and mathematical method a steady state system analysis will involve simultaneous solutions of algebraic equation. So if you have a steady state system all that you have to do is you have to solve a set of algebraic equation equations whereas in dynamic system analysis. That means an analysis where time comes into picture okay. The performance variation against time this involves simultaneous solution of partial differential equation.

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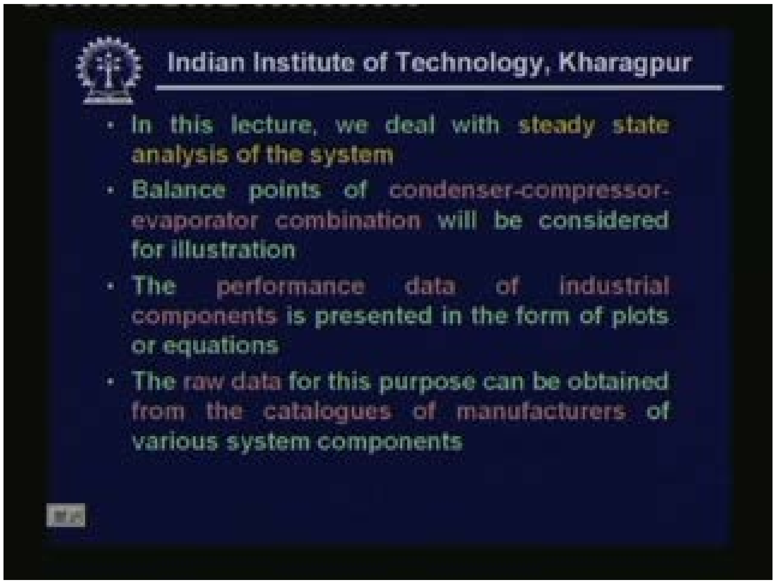

So in this lecture we deal with steady sate analysis of the system. That means we will be solving only algebraic equations. So balance points of condenser compressor evaporator combination will be considered for illustration. So I take a simple example, as I mentioned introduction,

I will show the concept by using very simple example. The performance data of industrial components is presented in the form of plots or equations. The ray raw data for this purpose can be obtained from the catalogues of manufacturers of various system components. Let me make one thing very clear here that you require in order to perform complete system analysis. You have to have some raw data on individual components.

For example for the compressor how the mass flow rate of the actual compressor actually industrial compressor. How does it vary with evaporator temperature? How does it vary with compressor temperature etcetera okay. So we have evaluated the mass flow rate etc using a some kind of idealized concept. And we have evaluated the volumetric efficiency and calculated the mass flow rate etcetera okay. But in actual compressor there will be some other deviation which cannot be considered in a theoretical analysis. So the performance of actual compressors will be slightly different from the theoretical analysis okay. So normally for complete system analysis it is better to take the values or the data applied by the manufacturer which is generated from the actual test conducted on the components okay. So from actual test data on the components you can fit equation or you can generate curves and using these curves we can do the complete system analysis okay. So that is the procedure generally followed.

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So first let us look at the performance characterizes of reciprocating compressor. Basically in this example we have we are considering a reciprocating compressor and the equation is generally holds good for hermetic type of compressor. So for the purpose of balancing what is done here is the refrigeration capacity is required as the function of evaporator and condenser temperature. So we what we do is we always plot take the refrigerant capacity as a required performance parameter okay. And express this in terms of the other individual parameter okay. So let me show the variation of refrigerant capacity with other individuals parameters.

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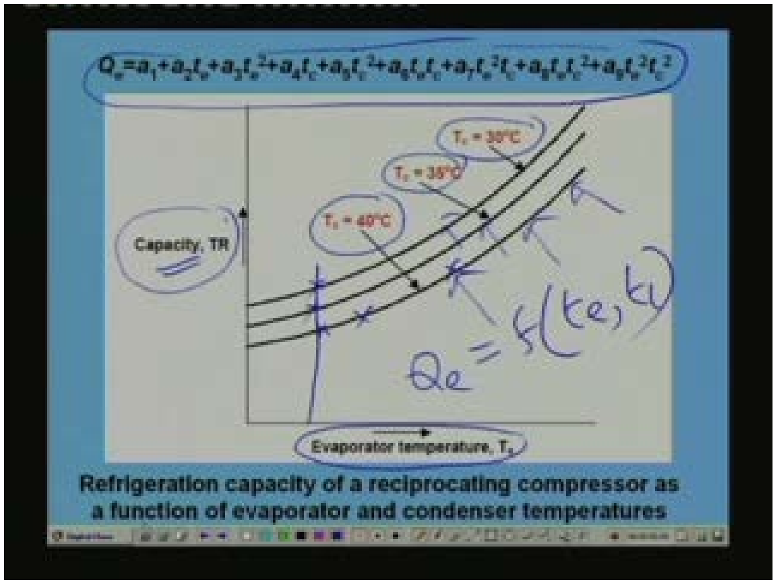

In fact you have seen this earlier. So this graph shows the performance of a industrial reciprocating compressor and here capacity is plotted on Y-axis and on X-axis you have the evaporator temperature and capacity is given for different condenser temperatures okay. You can see one thing that you can notice here is for example for a given condenser temperature. Let us say a condenser of forty degree centigrade the capacity increases as the evaporator temperature increases okay. The same thing is also observed in case of the theoretical analysis also. That means an actual component the trends will remain more or less the same as that of theoretical analysis but the values will be slightly different okay.

And you can also see here that at a given evaporator temperature as the condenser temperature reduces the capacity increase okay. So these aspects we have considered we have already discussed while discussing the reciprocating compressor. So now you have three curves okay for three different condenser temperature and as a function of evaporator temperature. Now you can, for each of the curve you can fit an equation. For example let us say that Qe is the capacity of the systems so Qe can be expressed as a function of te and tc okay. Generally it will be algebraic equation polynomial equation for example, so for this kind of a compressor. It is shown that you can represent the performance characteristics by this equation okay. And this equation involves nine constants and it also involves evaporator and condenser temperature. So we have to in order to find the constants we have to know the data at for example nine points okay. For example let us say that I have.

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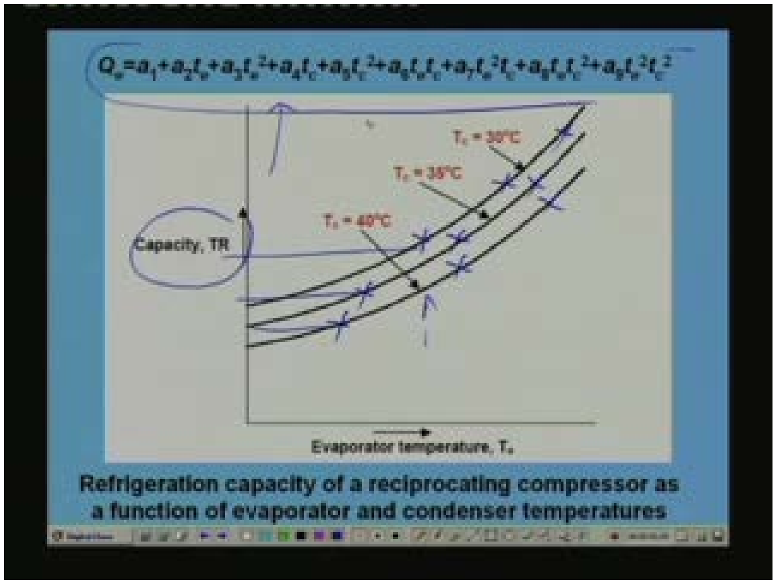

So using this, let us say I take three points each for three different temperatures the condenser temperatures and different evaporator temperatures. So you have total of nine points okay and at these nine points i know nine values of capacity okay. So using these point data we can then we can use this equation since you have nine points and in this equation we have nine unknowns these nine unknowns are the nine constants. So if you simultaneously solve these nine equations you can find out the constants a one to a nine okay.

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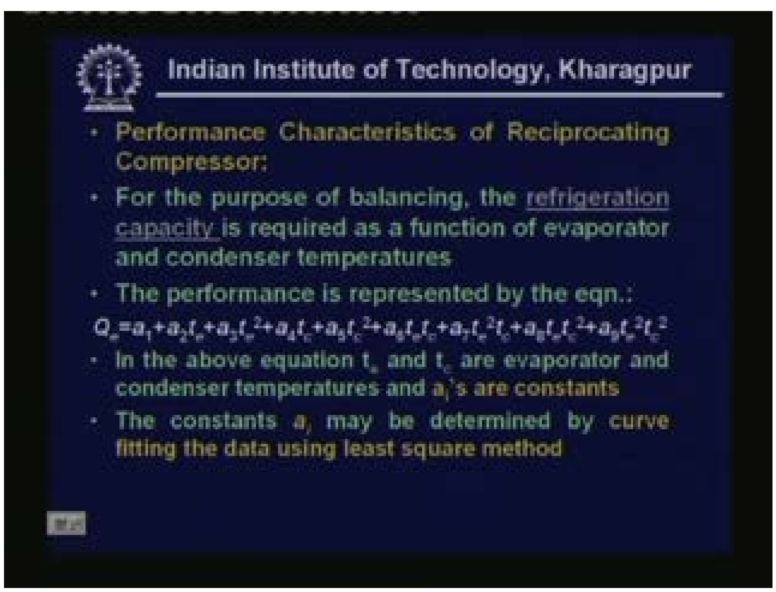

So the as I said the performance is represented by the equation Qe is equal to a one plus a two the plus a three the square plus a four tc plus a five tc square like that okay. You have a six the tc several terms okay. So there are nine terms here and nine constants so in the above equation te and tc are evaporator and condenser temperatures and ai. As I said are constants. The constants ai may be determined by curve fitting the data using least square method or you can also do it by having a nine nine point data and simultaneous is all in the equations okay.

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Now let us look at the performance characteristic of the condenser. Representing the actual performance of the compressor is quiet complex as it involves de-superheating condensing and sub cooling zones. In fact this point we have discussed while discussing the design of the condenser. In an actual condenser you have three distinct zones the first zone is where single phase heat transfer takes place and the refrigerant vapor get de-superheated by rejecting heat to ambient okay. During that process its temperature reduces then it enters into the two phase region where condensation takes place. So you have a phase change process okay. So you can also have depending upon the operating conditions a third zone where the refrigerant liquid undergoes sub cooling okay. Again this is a sensible transfer process so you have to sensible transfer processes and one latent heat transfer process.

And as you know when you are using a pure refrigerant the refrigerant temperature remains constant during the phase change process. That means during the condensation process but its temperature varies during the de-superheating and sub cooling regions. So the actual analysis of a condenser you must consider all these three zones okay. So temperature variation has to be considered and you have to calculate area required for the first zone area required for the second zone area required for the third zone like that okay. This is what is done in the design of actual condensing equipment okay. But most of the time for the sake of simplicity what is done is we assume that the temperature of the refrigerant remains constant throughout the condenser and throughout the condenser only condensation takes place okay. That means the de-superheating and sub cooling zones are also considered to be condensing zone okay.

What is the advantages of making this kind of an analysis assumption if we make this kind of an assumption on the refrigerant side you have a single temperature okay. Once you have a single temperature on the refrigerant side and a single heat transfer coefficient as that of the condensing heat transfer coefficient okay. So you on the refrigerant side all that you have to do is find out the condensing heat transfer coefficient and you know the condensing temperature okay. So this will considerably simplify the analysis right this is what is done here also okay. This is done as I said to simplify the problem. But remember that in an actual case the actual design will be slightly different because of the other two zones okay.

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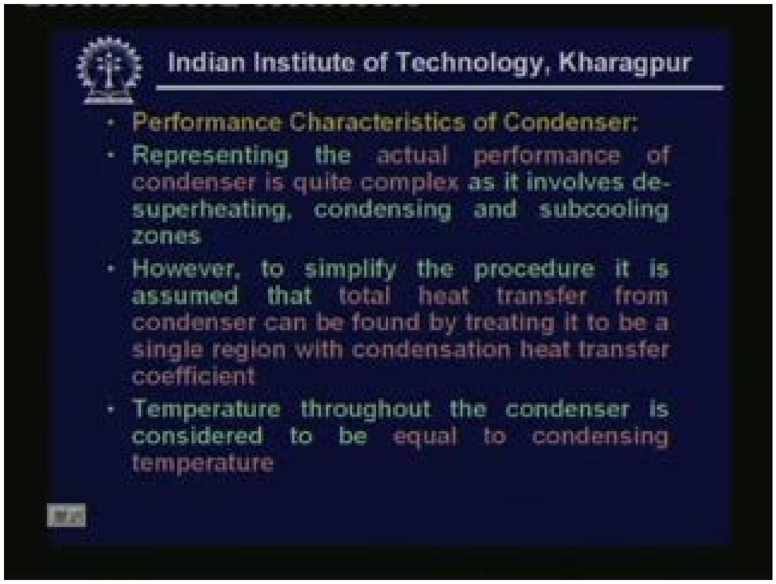

So as I said however to simplify the procedure it is assumed that total heat transfer from condenser can be found by treating it to be a single region with condensation heat transfer coefficient in the, in fact the justification for this was given while discussing the condensers and temperature throughout the condenser is considered to be equal to condensing temperature.

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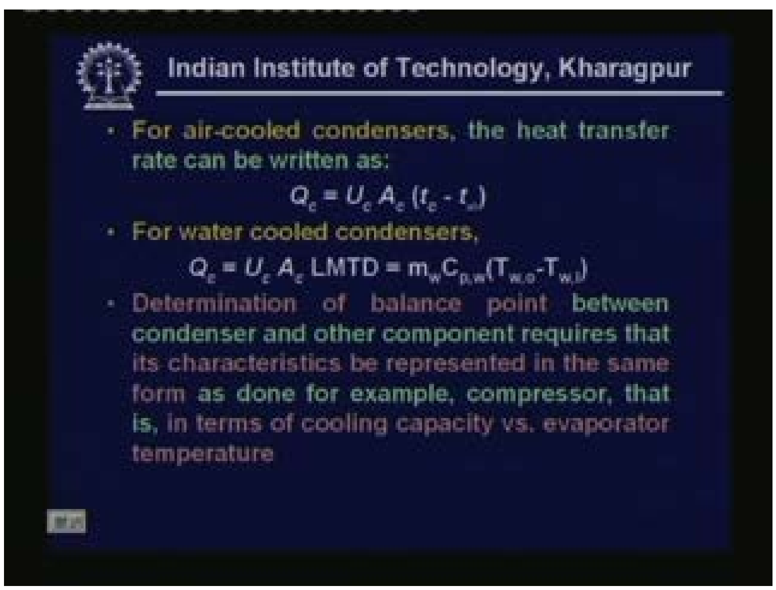

For air cooled condensers the heat transfer rate can be written as Qc is equal to Uc Ac into tc minus t infinity where Uc as you know is the overall heat transfer coefficients for the condenser. Ac is the area of the condenser and tc is the condensing temperature and t infinity is the ambient temperature okay. This is the equation which one can use for air cooled condensers whereas for water called condensers one can use the equation like this Qc is equal Uc Ac into LMTD where LMTD is the log mean temperature difference. This in turn is equal to mwCpw into T wo minus Twi where mw is the mass flow rate of the cooling water Cpw is the specific heat of the cooling water Two and Twi are the exit and inlet temperatures of the cooling water okay. Now determination of balanced point between condenser and other component requires that its characteristics be represented in the same form as done. For example compressor okay, that is in terms of cooling capacity verses evaporator temperature okay.

So for if you are using the balance point approach for complete system analysis what we have to do is we have to express all the characteristics of the components in terms of common parameters okay. For example if you take the refrigeration capacity as a required performance parameter. And if you want to express that in terms of the evaporator temperature then all the component performance characteristic should be expressed in terms of refrigerant capacity and evaporator temperature okay.

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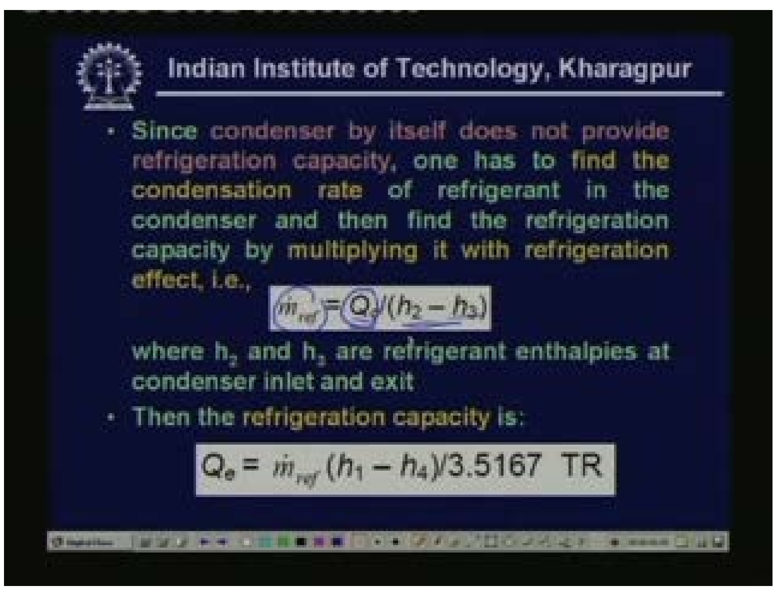

However condenser by itself does not provide refrigerant capacity okay. Compressor condenser cannot provide refrigerant capacity alone. So one has to find the condensation rate of the refrigerant in the condenser and then find the refrigeration capacity by multiplying it with refrigeration effect. That means what we do is first we find out Qc where Qc is the okay so first we have to find out Qc Qc is the heat transfer rate in the condenser from this Qc we find out the mass flow rate of the refrigerant. In the condenser or the condensation rate the condensation rate of the refrigerant is given by m dot subscript ref. This is nothing but Qc divided by h two minus h three where h two and h three are inlet and exit enthalpies of the refrigerant okay. So if you know h two and h three and if you know Qc you can find out what is the mass flow rate of refrigerant through the condenser.

Now under steady state because that is what we are trying to do we are trying to predict the performance in the steady state. The mass flow rate through the condenser is same as the mass flow rate through the evaporator okay. So once you find out what is the mass flow rate through the condenser these are same mass will flow through the uh evaporator in the same time okay.

So you also know the mass flow rate through the evaporator. So once you know the mass flow rate through the evaporator we can find out what is the refrigerant capacity by multiplying the mass flow rate into the refrigeration effect okay. So that is what is done here.

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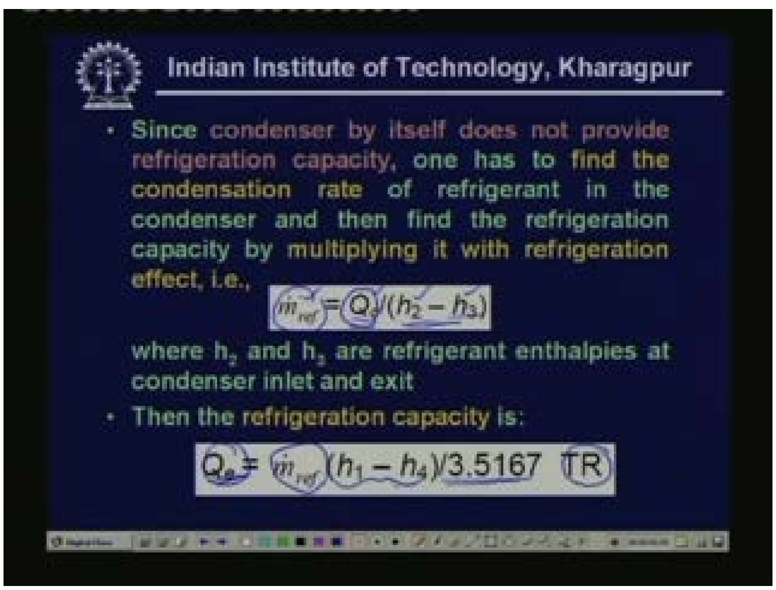

We finally we need the refrigerant capacity Qe is equal to m dot ref this is nothing but the condensation rate in the condenser multiplied by h one minus h four where h ne minus h four is the refrigeration effect one an dh four are the exit and inlet enthalpies of the refrigerant okay.

We are dividing this by three point five one six seven because here all the refrigerant capacities are expressed in terms of tones of refrigeration okay. That is the reason why we are dividing in terms of three point five one six seven okay. So here the units of mass flow rate should be kg per second and units of enthalpy should be in kilo joule per kg okay.

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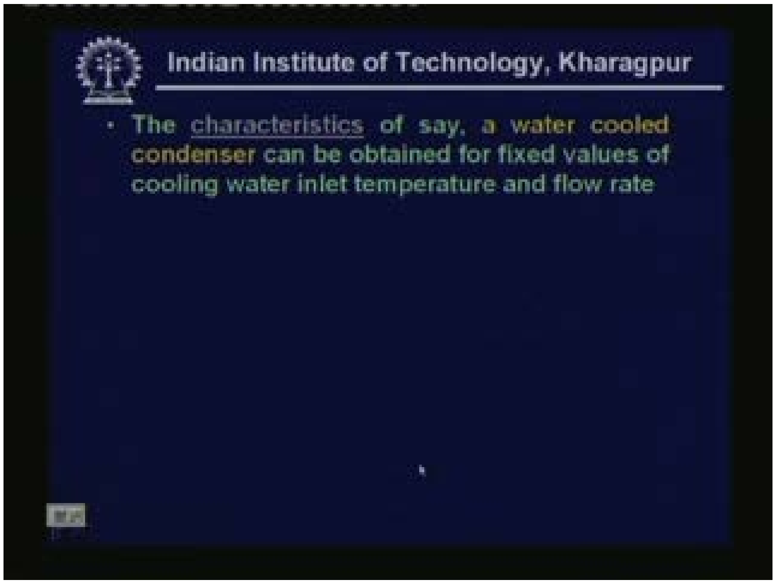

Now the characteristics of say a water cooled condenser can be obtained for fixed values of cooling water inlet temperature and flow rate. In this example, I have, I will consider only a water cooled condenser. Of course the same similar analysis can also be applied to an air cooled condenser also okay. So for the purpose of illustration we have considered a water cooled condenser here. So the as I said water cooled condenser characteristics can be obtained for fixed values of cooling water inlet temperature and flow rate okay. So let me show the graph first.

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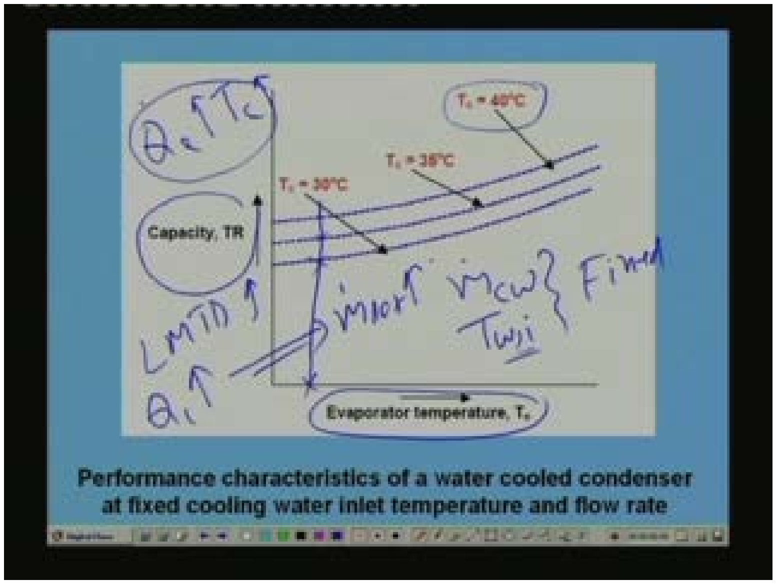

For example this is the typical performance characteristics of a water cooled condenser at fixed cooling water inlet temperature and flow rate okay. That means here mass flow rate of cooling water and cooling water inlet temperature these two are fixed okay. And here we plot refrigeration capacity in terms of evaporator temperature okay. One thing you can notice here is that at a given evaporator temperature. Let us say some evaporator temperature as the condenser temperature increases the capacity increases.

That means Qe is increasing as Tc is increasing. Why the, why Tc as Tc increases Qe increases because we have fixed the mass flow rate of the cooling water and we have also fixed the, a water inlet temperature. So when you are increasing the condenser temperature. Then your log mean temperature increases okay. Once log mean temperature difference increases Qc increases okay. Once Qc increases mass flow rate of refrigerant increases okay. So this implies mass flow rate of refrigerant increases once mass flow rate of the refrigerant increases the capacity of the system increases okay. And you can also see here that for a given condenser temperature. For example say thirty degree centigrade as the evaporator temperature is increasing capacity is increasing. That means Qe is increasing as Te is increasing why is it? So because as Te increases your heat rejection rate decreases okay. That means per tone of capacity less heat has to be rejected in the condenser okay, if you have a fixed condenser. That means the area of the condenser is fixed. So the heat rejected per tone of the refrigeration reduces means for a given condenser size more capacity is possible. Because the condenser rate will be higher okay, that is the reason why you get higher capacity okay.

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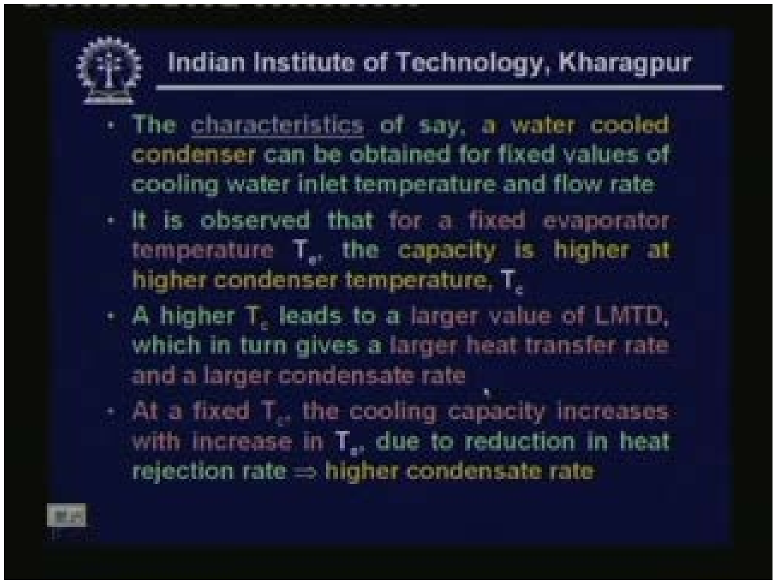

So it is as I said, it is observed that for a fixed evaporator temperature Te the capacity is higher at higher condenser temperature. A higher condenser temperature leads to a larger value of LMTD which in turn gives a larger heat transfer rate and larger condensate rate. And as I have already meant mentioned at a fixed condenser temperature. The cooling capacity increases with increase in evaporator temperature. Due to reduction in heat reduction rate this is due to higher condenser rate this leads to higher condensate rate which will give you higher capacity.

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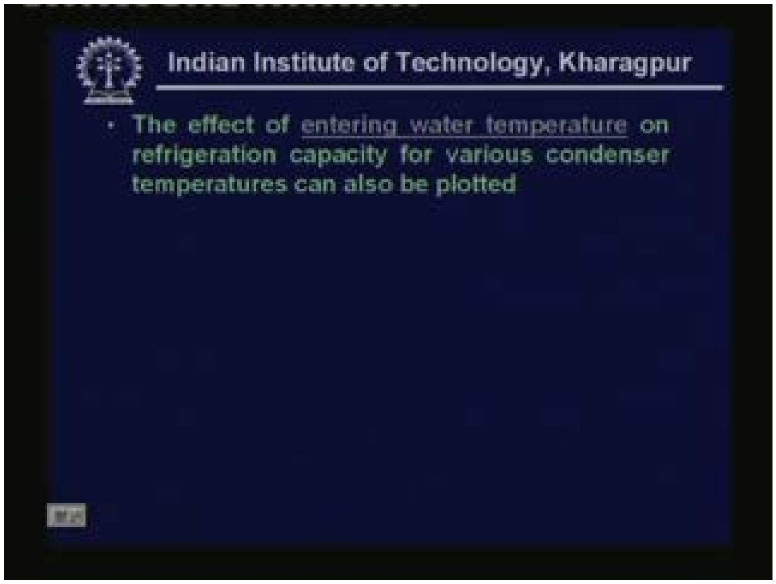

Now the effect of entering water temperature on the refrigeration capacity for various condenser temperatures can also be plotted okay. The last curve is for the fixed water inlet temperature and fixed flow rate okay. We just varied evaporator temperature and condenser temperature and we got the capacity of the system you can also study what is the effect of condenser water inlet temperature. That means the cooling water inlet temperature on the capacity of the system okay.

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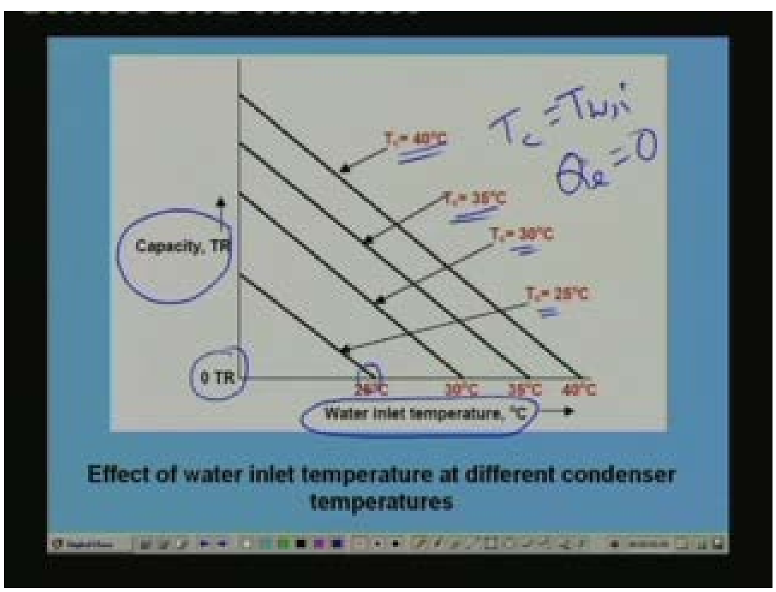

So if you plot this you will find that it will be something like this okay. This curve shows on the x-axis you have the water inlet temperatures on the y-axis you have the capacity of the system and the capacity is plotted for different condenser temperatures okay. And here the capacity is zero it starts with zero okay. The origin is zero one thing you can immediately notice here is that when the cooling water inlet temperature is same as the condenser temperature capacity becomes zero okay. That means when Tc is equal to T water inlet temperature Qe is equal to zero this is obviously equal to zero. Because once the cooling water temperature is same as the condenser temperature no heat rejection can take place from the condenser okay. Since no heat rejection can take place there will be no condensation okay. Once there is no condensation there will not be any liquid mass flow rate liquid right as a result there will not be any refrigerant capacity okay. That is the first observation second observation.

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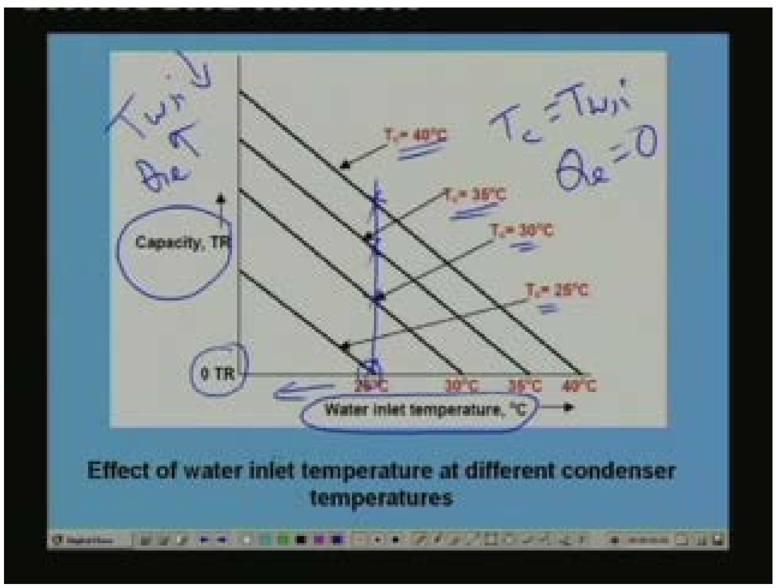

Is that for a given condenser temperature for example same twenty five degree centigrade as the water inlet temperature reduces capacity increases okay. That means as Twi reduces Qe increases

again the reason is similar as the Twi reduces for a given condenser temperature your LMTD increases. So the heat transfer rate in the condenser increases. That means condensation rate increases condensation rate increases means mass flow rate increases mass flow rate increases means capacity increases okay.

Similarly at a given water inlet temperature as the condenser temperature increases capacity increases. Again the reason is same once the condenser temperature increases for a fixed water inlet temperature LMTD increases heat transfer rate increases. Hence capacity increase you can see that here the curves are almost straight lines okay. And, so they are almost parallel to each other okay, for different condenser temperature curves.

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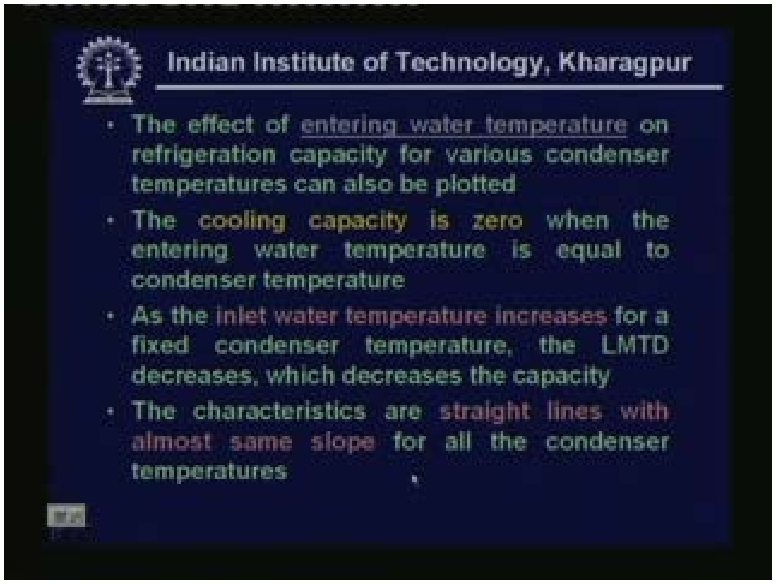

So as I mentioned the cooling capacity is zero when the entering water temperature is equal to condenser temperature. As the inlet water temperature increases for a fixed condenser temperature the LMTD decreases, which decreases the capacity. The characteristics are straight lines with almost same slope for all the condenser temperatures.

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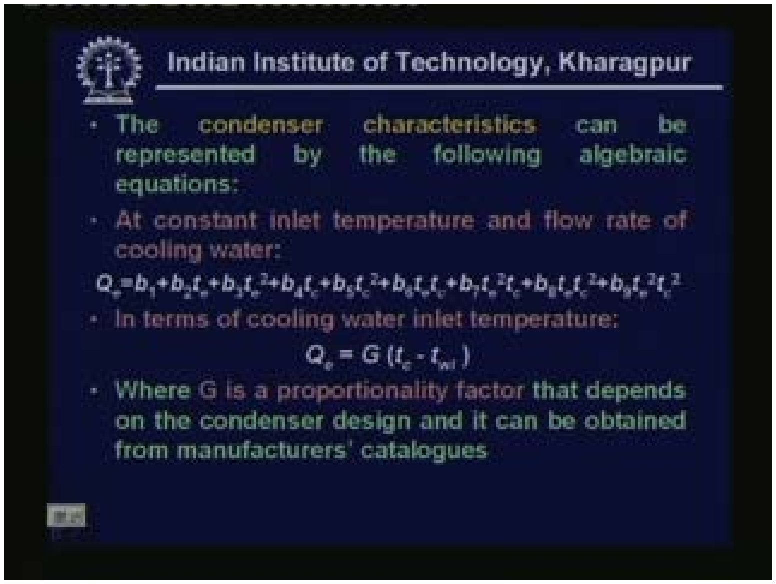

The condenser characteristics can be represented by the following algebraic equations okay. Just like your compressor you can also represent the condenser characteristics by an algebraic equations. First at constant inlet temperature and flow rate of cooling water. You can get an equation like this polynomial equation Qe in terms of evaporator temperature TE and condenser temperature Tc again this equation has nine terms. So you have nine constants b one to b nine okay.

So again you have t use method of least squares or you can also have nine point data and solve the equation to obtain the constant b one to n nine and in terms of cooling water inlet temperature. You can also write Qe is equal to G into Tc minus Twi where Tc is the condenser temperature Twi is the water inlet temperature and G is the proportionality factor. It is units are kilo watt per Kelvin or tone per Kelvin and the value of G depends upon the condenser design and it can be obtained from manufacturers catalogues okay.

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Now let us look at the performance characteristics of the evaporator a refrigerant evaporator is also a heat exchanger just you know that it like heat exchanger just like condenser here the evaporator is considered to be a brine chiller okay. So what we have considered in this particular example is that evaporator is brine chiller. Brine chiller means on the external fluid side you have a brine flowing okay. So refrigerant extract heat from the brine as you know is the solution of water and the salt and normally brines are used where that required temperatures are lower than zero degree centigrade if you use the pure water it may it will freeze right. Once the evaporator temperature falls below zero degree centigrade. So when you want refrigeration at sub zero temperature one can use brines okay. So the evaporator we have considered here is a brine chiller. That means you send a brine to the evaporator brine gives heat to the refrigerant and it gets chilled okay. So what you get out of the brine chiller is a chilled brine right.

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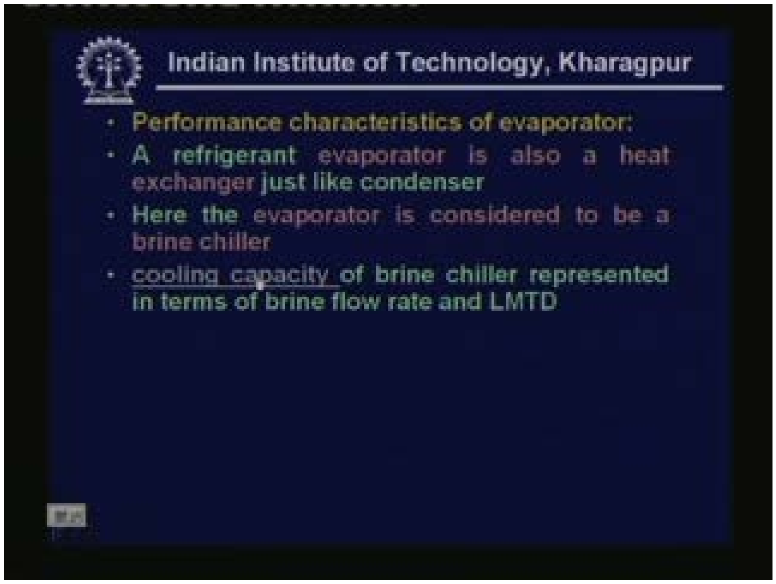

The cooling capacity of brine chiller can be represented in terms of brine flow rate and LMTD.

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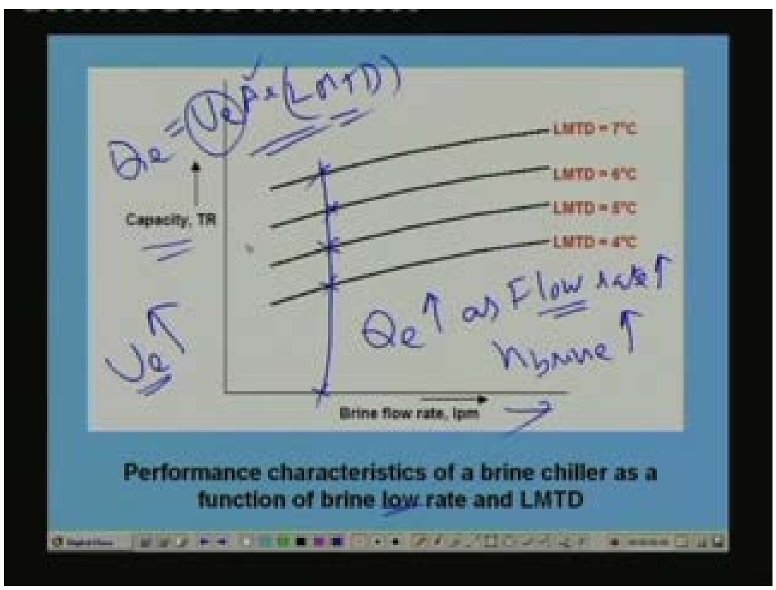

For example if you take a commercial brine chiller you can get this kind of capacity curves. This is the performance characteristics of a brine chiller as a function of brine flow rate and LMTD okay. This should be flow rate so as the brine flow rate increases you can see that the capacity increases for a given LMTD okay. That means capacity Qe increases as flow rate increases. Why the capacity increases, because the flow rate increases heat transfer coefficient on the brine side increases okay. h brine increases as the flow rate increases once h brine increases overall heat transfer coefficient of the evaporator increases okay. Once overall heat transfer coefficient increases since your keeping the LMTD constant obviously your Qe increases. Because QE is equal to Ue AE into LMTD right or the brine chiller LMTD is constant Ae is constant Ue is increasing. So obviously capacity increases right similarly using this equation it can be very easily shown that at a given brine plow rate as the LMTD increases the capacity increases okay. So this is easy to understand.

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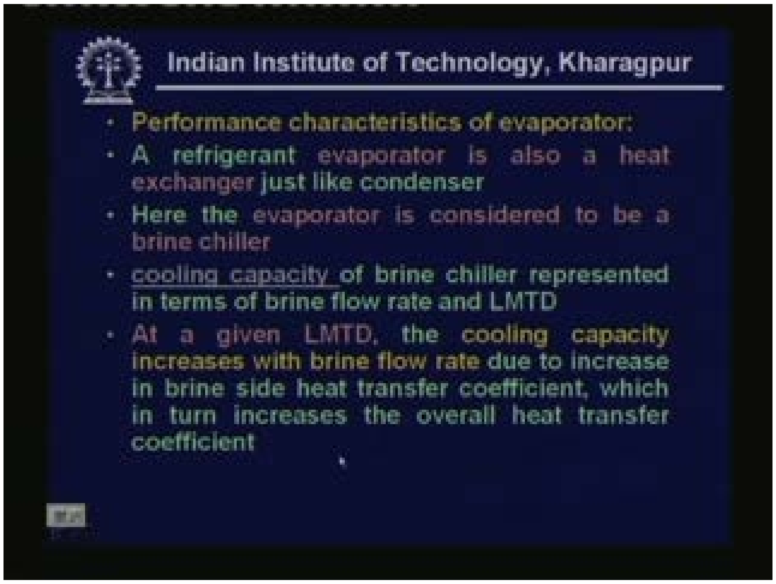

So okay, as I said at a given LMTD the cooling capacity increases with brine flow rate due to increase in brine side heat transfer coefficient which in turn increases the overall heat transfer coefficient.

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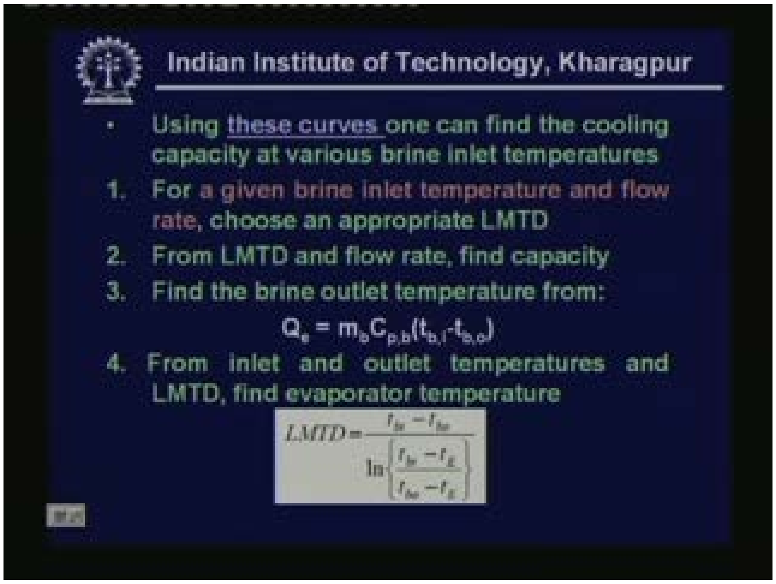

Using these curves one can find the cooling capacity at various brine inlet temperatures okay. How do you find that for a given brine inlet temperature and flow rate choose an appropriate LMTD oka. So let me explain with the help of the curves.

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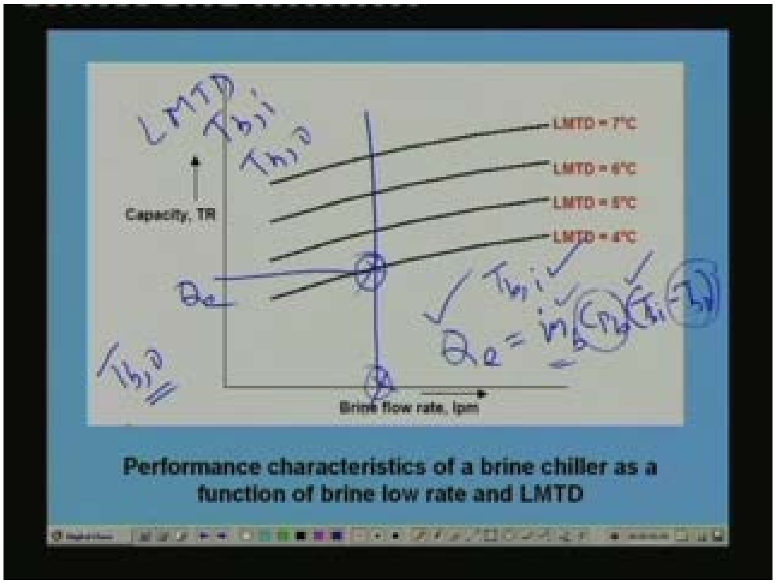

Let us say that we know the flow rate okay. Let us say this is the flow rate and you choose some LMTD okay. So let us say that we have chosen an LMTD of four degree centigrade and this is the brine flow rate. And if the brine inlet temperature is also known, let us say that t brine inlet temperature is known this is the brine inlet temperature. This is known to us, then you can write from energy balance you can write Qe is equal to mass flow rate of the brine into Cp of the brine into brine inlet temperature minus brine outlet temperature okay. So since your, you know the flow rate okay. m dot b is known and LMTD is known. So you can find out Qe right. So Qe is known to us known to you and m dot b is known to you Cpb can be obtained from the property data Tbi is fixed. So you can find out Tbo okay. So first you can find out what is the outlet temperature of the brine once you know the inlet and outlet temperatures. And you also know the LMTD. So from LMTD brine inlet temperature and brine outlet temperature we can find out what is the evaporator temperature okay.

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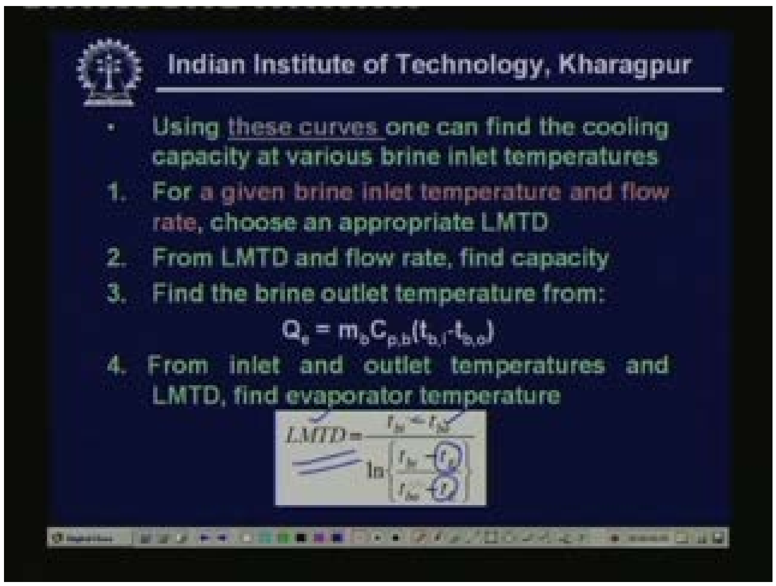

That is what is done here. So as I said for a given brine inlet temperature and flow rate choose an appropriate LMTD. Then from LMTD and flow rate find the capacity using the characteristics curves and find the brine outlet temperature using the equation Qe is mb cpbi into tbi minus tbo

from inlet and outlet temperature and LMTD find evaporator temperature okay. And as you know for this brine chiller the expression for LMTD is like this where tbi is known to you known to us tbo is computed te has to te obtained okay. So this is known to us so there is only one unknown, so you can find out what is the evaporator temperature.

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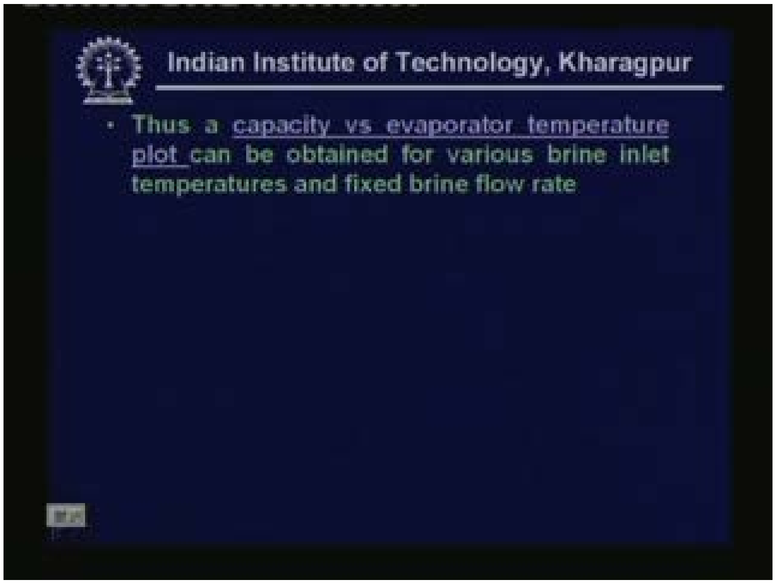

So thus a capacity verse evaporator temperature plot can be obtained for various brine inlet temperatures and fixed brine flow rate okay. So this manner in this manner what we can do is you can keep the brine flow rate fixed. And then take another brine inlet temperature okay.

Once you take another brine inlet temperature you get again different evaporator temperature okay. So likewise you can generate a data where you can express the evaporator temperature in terms of the, I am sorry, the evaporator capacity in terms of the evaporator temperatures and brine inlet temperatures okay.

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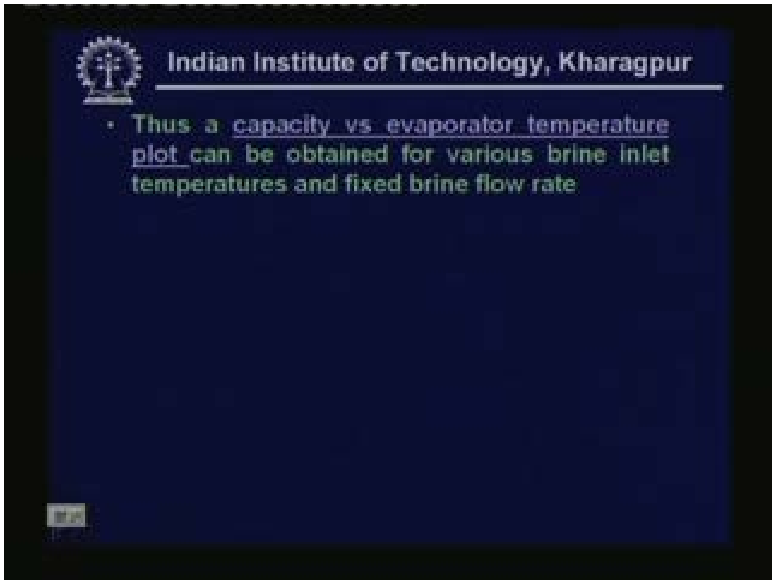

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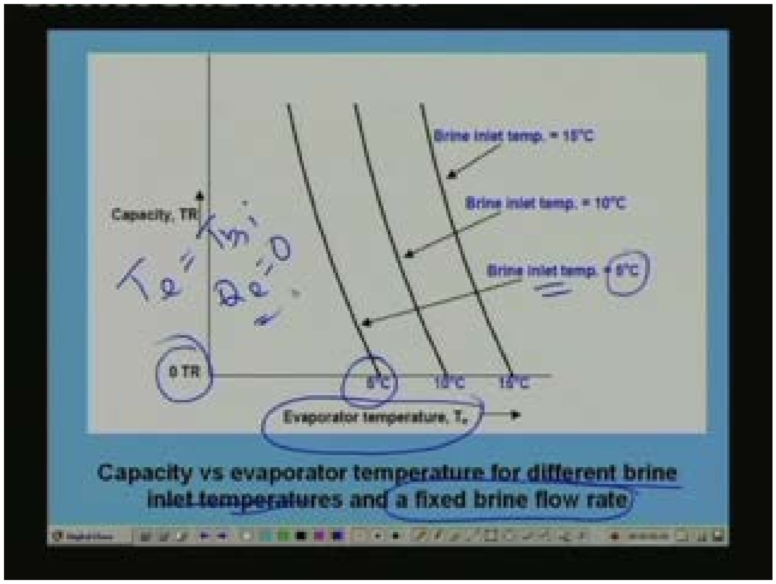

So if you plot this you will get this kind of, this is capacity verses evaporator temperature for different brine inlet temperatures okay. And evaporator temperature at a fixed brine flow rate okay. So brine flow rate is fixed right again if you look at the characteristics one thing that is immediately you can notice here is that when the brine inlet temperature for example five degree centigrade is equal o the evaporator temperature then the capacity becomes zero okay. That means when Te is equal to Tbi Qe is equal to zero this is obviously the case because there is no temperature difference between the brine and the evaporator. So there cannot be any heat transfer okay, one, once there is no heat transfer from the brine to the refrigerant the capacity will be zero okay. And what happens when the evaporator temperature reduces for a given brine inlet temperature? Obviously as the evaporator temperature reduces for a given brine inlet temperature. Your temperature difference between the brine and evaporator increases. So the capacity increases okay.

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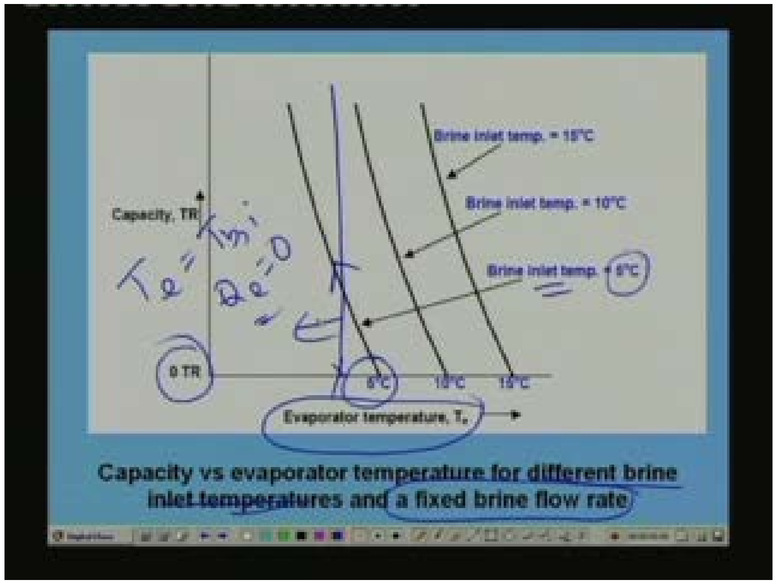

So that is what is shown here so as you move in this direction capacity increases as the evaporator temperature reduces for the given brine inlet temperature. Similarly at a given for example at a given evaporator temperature as the brine inlet temperature increases temperature difference between brine and refrigerant increases. So capacity increases okay. So these are you can easily observe from these curves.

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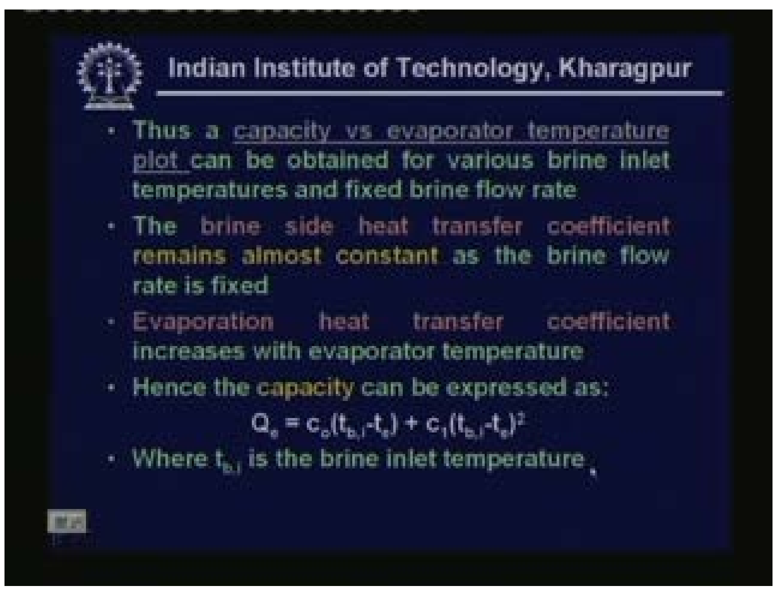

One thing is since we have fixed the brine flow rate constant the brine side heat transfer coefficient remains almost constant okay. Because the flow rate is fixed and the evaporator is fixed means the velocities diameter velocities etcetera are fixed. So the heat transfer coefficient remains more or less constant. If there is any slight variation that may be because of the temperature variation which is normally negligible okay. However evaporation rate evaporation heat transfer coefficient increases with evaporator temperature okay. As a result the capacity can be expressed as this equation Qe is equal to C not into tbi minus te plus c one into tbi minus te whole square okay. Again here tbi and te are brine inlet and evaporator temperatures and C not and C one are constants which have to be obtain either from the regression analysis either from least square method or from the point data okay, a two point data.

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Now will the last components is the expansion valve the flow characteristics of the expansion valve play and important role in deciding the conditions achieved by the refrigeration system. However what we do is for simplicity sake here we assume that the expansion valve is capable of providing sufficient mass flow rate at all condenser and evaporator temperatures okay. You can also bring in the expansion valve into the analysis and you can again have see what is the effect of the variation on the system performance okay. That means you will have to basically stimulate the four components system performance okay. But for simplicity what we assume here is that we have an ideal expansion device which will always provide the required flow rate at different evaporator and condenser temperatures okay. That means it will satisfy our requirement under all conditions okay.

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Now let us do balancing of components okay. First let us do the balancing of compressor and condenser okay. This is known as the condensing unit the combination of compressor and condenser is called as condensing unit. This unit draws refrigerant from the evaporator compresses. It condenses it into liquid refrigerant which is then fed to the expansion valve. The condensing unit is available as a packaged unit with matches set of compressor motor and condenser along with reservoirs and controls. This may be air cooled or water cooled unit which may be installed as an outdoor unit okay.

So this as you can see that combination of compressor and condenser along with controls and the motor is called as the condensing unit okay. The condensing units are generally available of the self as packaged unit okay. That means you want the condensing unit for let us say ten system okay. It is available of the self you dint have to buy individual components and assemble them okay. So you can buy it then you can assemble the rest of the components all right and these conversing units will be balanced by the manufacturer himself okay. He will do the balancing himself.

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So performance of the condensing unit as function of evaporator temperature is obtained by combining the characteristics of compressor. And condenser temperature and flow rate of entering water to condenser are kept constant okay. So here what we are assuming is the inlet water temperature and the flow rate of cooling water both are constant and matching is obtained by superimposing compressor performance on condenser performance okay. Let me show you this.

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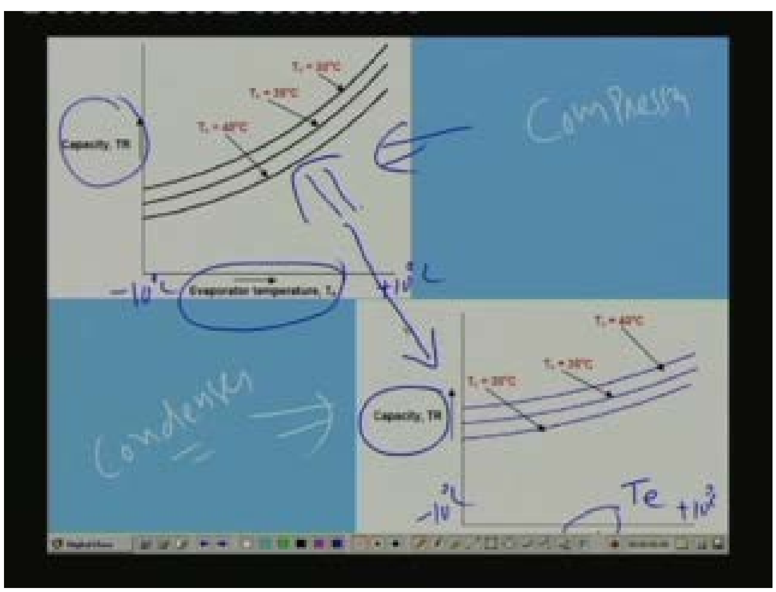

So we had in fact we have seen this is the, I have discussed these are the characteristics of the compressor okay, compressor characteristics right. And this is the characteristics of the condenser okay. One thing you should notice here is, here in both X and y-axis have to be same for both the units okay. So that is what is done here for example for compressor the Y-axis is for capacity and x-axis is evaporator temperature and for the condensing condenser also the y-axis has to be for capacity and x axis has to be evaporator temperature okay. Both have got to be same and the scales also have got to be same. For example if the evaporator temperature in this case is varying from let us say minus ten degree centigrade to plus ten degree centigrade. Here also it should vary from minus ten degree centigrade plus ten degree centigrade okay. It has to be exactly same axis similarly the capacity okay. Now then the matching between the condenser and compressor is obtained by simply super imposing this onto this okay.

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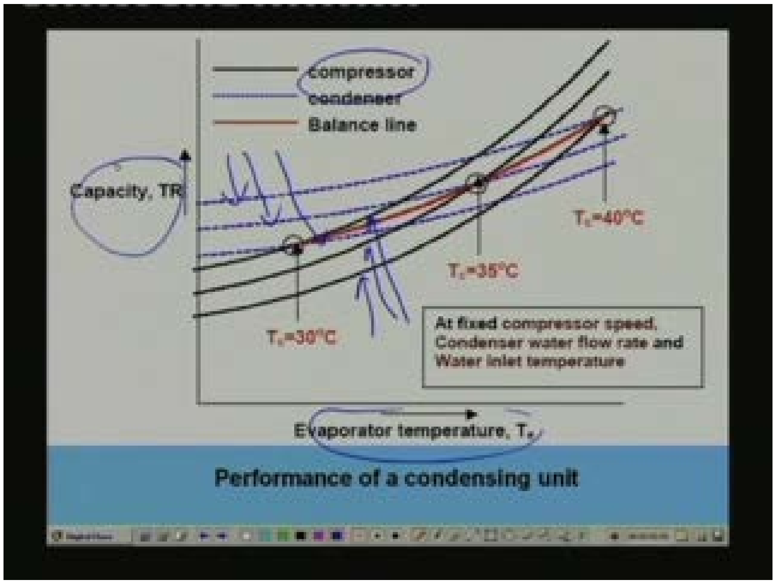

So if you super impose that you have to get this curve okay. You can see here that what we have simply done is we have superimposed the compressor characteristics okay. The black line on to the condenser characteristics curves that is the dashed blue lines okay. These are super imposed as I said when you are super imposing them the axis have got to be the same right. And how do you find the balance point we find the balance point from the points of intersection okay. So if you remember for the compressor this is thirty degree centigrade this is thirty five degree centigrade. This is just an example okay, it can be any temperature but thirty five and forty degree centigrade okay. And for the condenser this is thirty degree centigrade. This is thirty five degree centigrade and this is forty degree centigrade. Remember that here we are keeping the flow rate and the cooling water temperature inlet temperature constant. Now what are the balance points. Here the balance points are nothing but the points f intersection. That means you take the condenser length. For example a forty degree condenser line okay, where the condenser line at forty degree condenser temperature is intersecting with the compressor line at forty degree condenser temperature okay.

That is the balance point for forty degrees okay that is this point right. So at this point the forty degree condensing temperature lines of compressor and condenser are intersecting. So you get one balance point here and at this point now the compressor and condenser characteristic curves at thirty five degree condensing temperatures are intersecting okay. Similarly at this point thirty degree centigrade condenser temperature balance point okay. So if you join all these three points you get the balance line here okay. Or the characteristic curve for the conversing unit right and remember that this is at fixed compressor speed fixed condenser water flow rate and fixed condenser ka water inlet temperature okay.

And this red line is your balance or characteristic curves for the particular condensing unit okay. So that is how we have done the matching between the condenser. And the compressor in fact you can notice here that this principle is exactly same as what we have done in case of compressor and capillary tube okay. So we have taken the x and y-axis to be same for both the components and then we have super imposed a one graph on the other. And then from the points of intersection we could get the balance points same concept is applied here also right.

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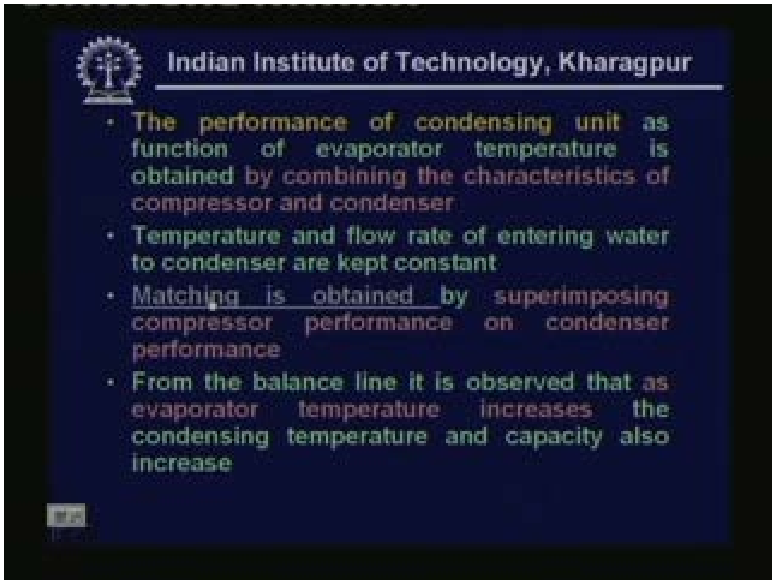

So from the balance line it is observed that as evaporator temperature increases the condensing temperature and the capacity also increase.

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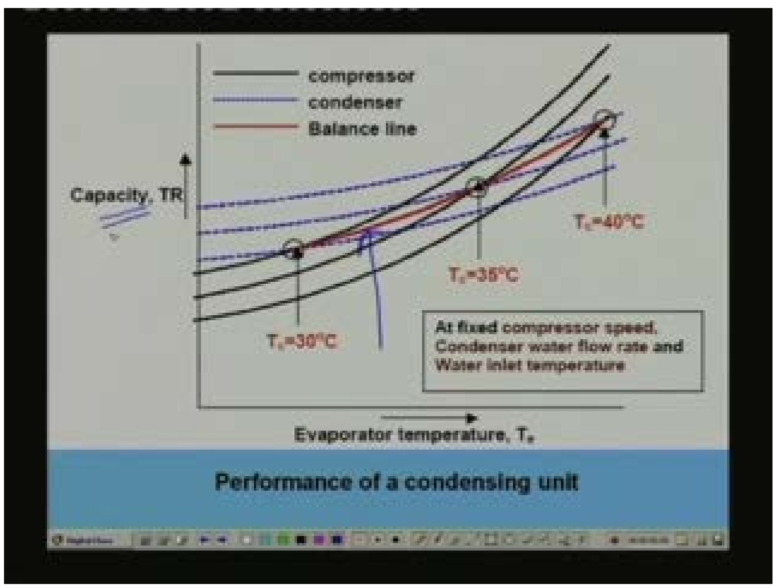

So that you can see here. So from this red line that is the balance line. This line you can see that as the evaporator temperature increases the capacity increases okay. At the same time as the evaporator temperature increases the balance condenser temperature also increases okay, and we know the reason why this happens.

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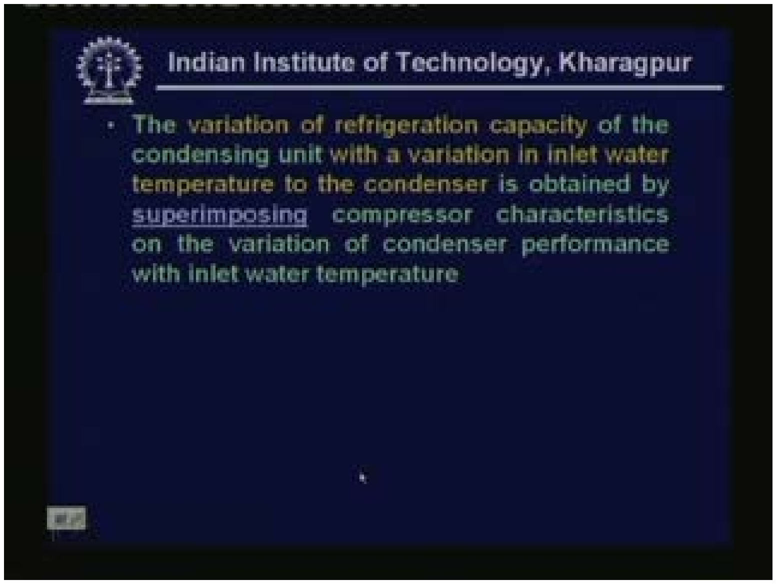

The variation of refrigeration capacity of the condensing unit with a variation in inlet water temperature to the condenser is obtained by superimposing compressor characteristics on the variation of the condenser performance with inlet water temperature okay. So you can also find what is the effect of the condenser water inlet temperature okay. This is done by again the principle of super imposing.

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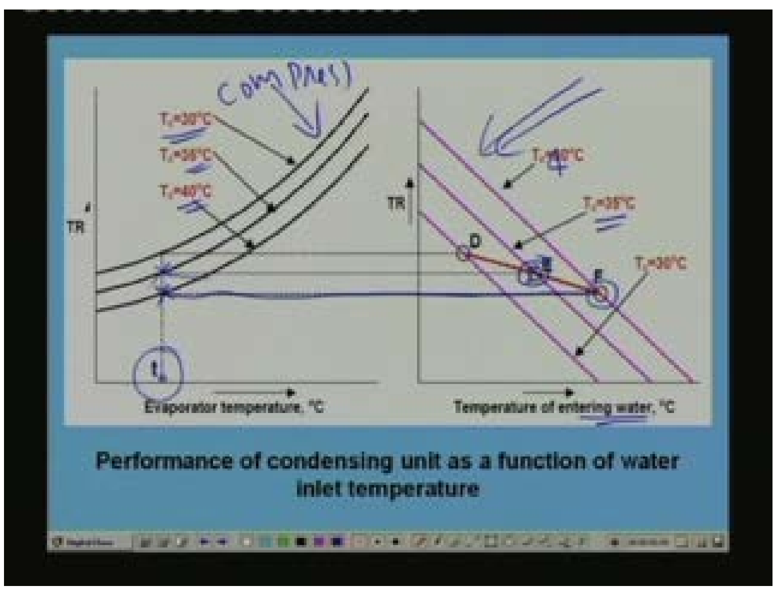

For example here this is what is done here this picture shows the performance of condensing unit as a function of water inlet temperature okay. So this as you know is the characteristic of the compressor okay. We have discussed before for the three different condenser temperatures of thirty degrees thirty five degrees and forty degree centigrade okay. And this also we have discussed this is the characteristics of the condenser as a function of water entering temperature okay, for different condenser temperatures right. Now how do u get the characteristics curve here. For example if you choose a evaporator temperature here right. Then you draw a vertical line let us say that your condenser temperature is forty degrees okay. So this vertical line intersects the forty degree line at this point.

So from this point you draw a horizontal line where this line intersects, I am sorry, this should have been forty degree okay. So where this line intersects the forty degree temperature line that is this line, that will give you the balance point for forty degree centigrade line. Similarly this point is for the thirty five condenser temperature line where if you draw a horizontal line where it intersects this thirty thirty-five degree line that will give you the another balance point. Similarly for thirty degree temperature line you can draw a horizontal line. And at this point this line intersects the thirty degree condensing temperature line in terms of cooing water inlet temperatures okay. So you can get very useful information from this one. For example, let us say that you also know this one okay.

And you will you also know the condensing temperature. The first information that you can get is what is the capacity right second thing is what should be the required water inlet temperature okay. For example for forty degree centigrade this has to be the condenser water inlet temperature. And for thirty five degree centigrade this has to be the condenser water inlet temperature. Similarly for thirty degree centigrade this has to be the condensing water inlet temperature. You can also do it in a reverse manner if the, you know this one okay. If you want to find out what is the balance evaporator temperature. That also can be done you have to draw a line from here okay. Then come this side and where the intersection coming go down and find the evaporator temperature okay. So that in the, that is how you can find out and one curve parameter is known the other balanced the other parameter at balanced point.

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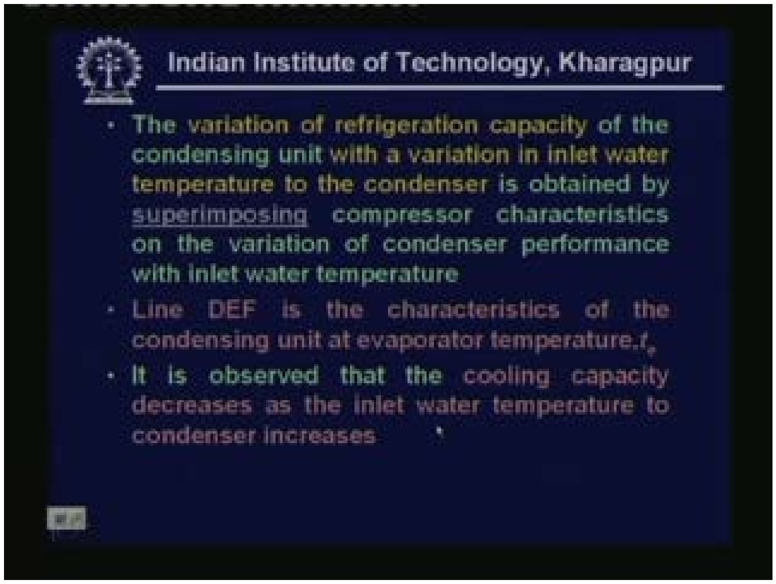

Okay, as I said line DEF is the characteristics of the condensing unit at evaporator temperature Teit is observed that the cooling capacity decreases as the inlet water temperature to condenser increases. Obviously as the inlet water temperature to condenser increases for a fixed condenser temperature the LMTD reduces once the LMTD reduces. The condensation rate reduces once the condensation rate reduces refrigerant capacity reduces okay. So one thing you can notice here is by having the individual capacity curves and by matching them we could get this kind of useful information okay. What happens when one parameter is changing what happens to the other parameter or what happens to the overall system performance? Okay, so that is the whole purpose of doing te complete system analysis okay.

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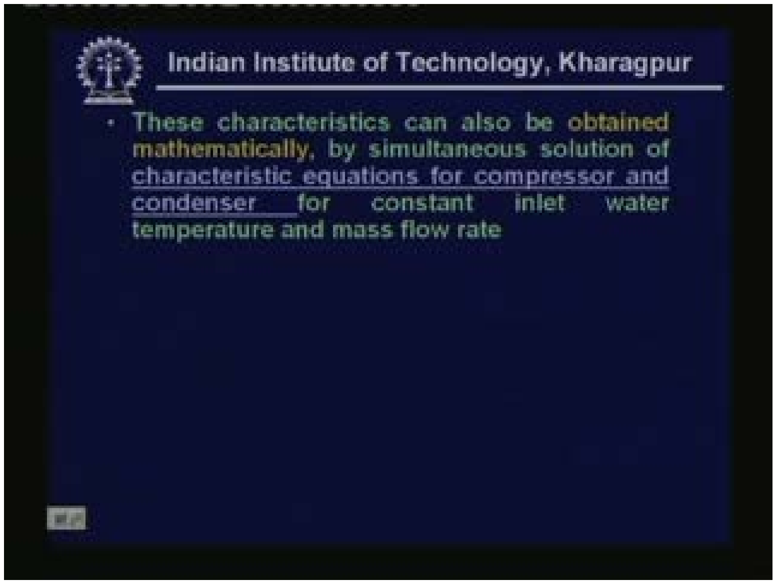

Now these characteristics can also be obtained mathematically by simultaneous solution, characteristics equation for compressor and condenser for constant inlet water temperature and mass flow rate. So far we have used graphical method for obtaining the balance point okay. Between the compressor and the condenser that means for the condensing unit the same balance point can also be obtained. If you know the characteristics equations for the compressor and the condenser okay. How can you do that?

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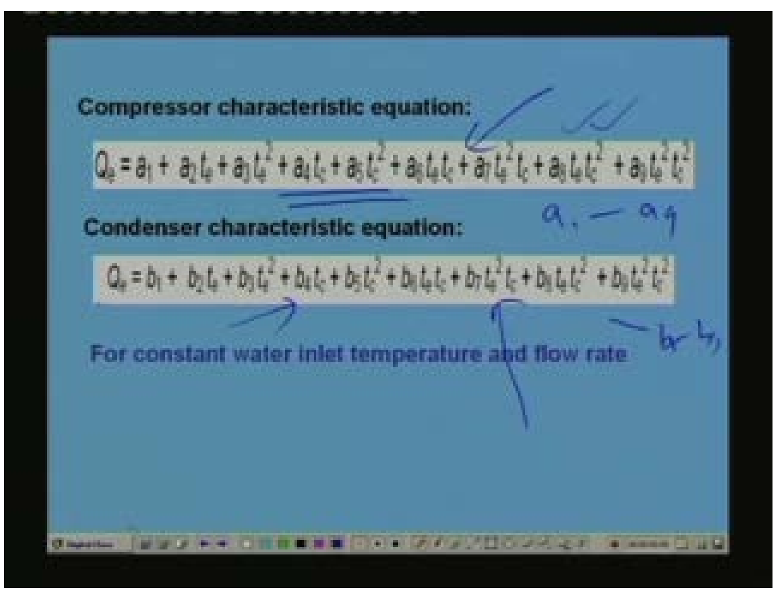

For example we have for the compressor this equation right. This is the equation for the compressor where you have nine constants and capacity is expressed in terms of evaporator and condenser temperature. Similarly of the condenser you have another equation which also consists of nine constants b one to b nine. Here you have a one to a nine and here you have b one to b nine and evaporator and condenser temperatures okay. So suppose we have this equations okay. You can get this equation from the compressor characteristics and you can get this equation from the condenser characteristics okay. Once you know the characteristics you also know the constants okay. Once you know the constants how do you find the balance point?

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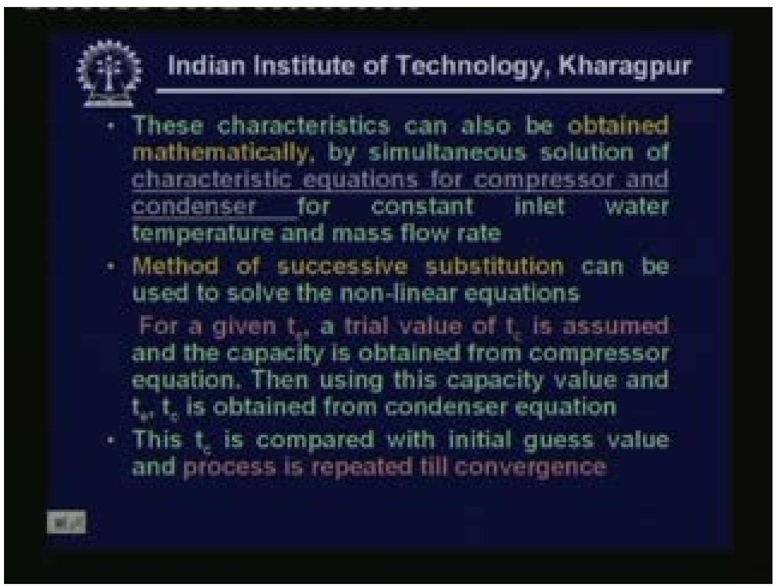

We use what is known as the method of successive substitution to solve these non linear equations. First what we do is for a given evaporator temperature we use a trial value of condenser temperature. And then using the compressor characteristic curves for example from the given evaporator temperature and the trial value of Tc we can find out what is the capacity.

Then what we do is we use this capacity and the evaporator temperature to find the condenser temperature from the condenser characteristic equation okay. And then we compare this calculated value of condenser temperature with the guess value of condenser temperature. If they are not same then we change the, we go for the second trial and we go on doing this iteration till we get a converged values okay. So this is the principle of successive substitution okay.

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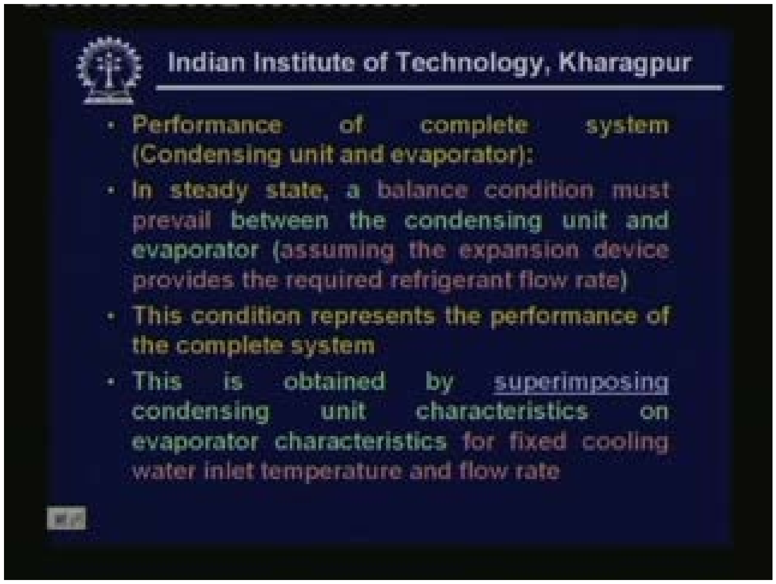

Now let us look at the performance of complete system. That means condensing unit and evaporator in steady state. The balance condition must prevail between the condensing unit and evaporator. This of course assuming the expansion device provides the required refrigerant flow rate and this is the assumption under which we are working out this example. This condition represents the performance of the complete system. This is obtained by super imposing condensing unit characteristics on evaporator characteristics for fixed cooling water inlet temperature and flow rate okay.

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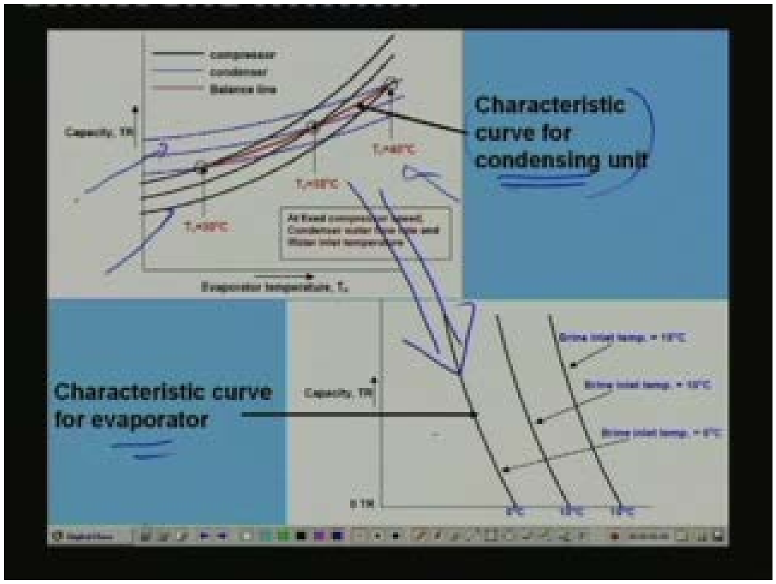

So just like we have done for the compressor and the condenser here again we super impose the performance characteristics of the condensing unit okay. Because we are trying to find the performance of the entire system okay. So we take the condensing unit characteristics and we super impose this curve on to the evaporator characteristic curve okay. This is the evaporator characteristic curve. Remember that this condensing unit characteristic curve we obtain by super imposing the condensing lines and the evaporator characteristic line okay. Now what we do is we superimpose this onto this right. And remember that this is at fixed compressor speed, fixed condenser water flow rate and condenser water inlet temperature whereas the evaporator temperature is for the fixed brine flow rate and different brine inlet temperatures.

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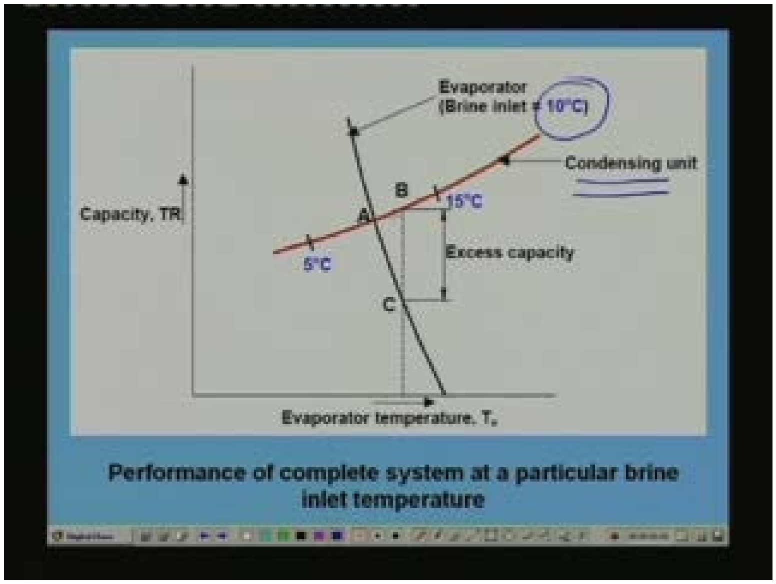

So if we superimpose this you get a curve of this kind okay. This I have shown for a one particular brine inlet temperature where that is of tem degree centigrade okay. And this is the condensing unit characteristic curve which what we have seen from the earlier this thing.

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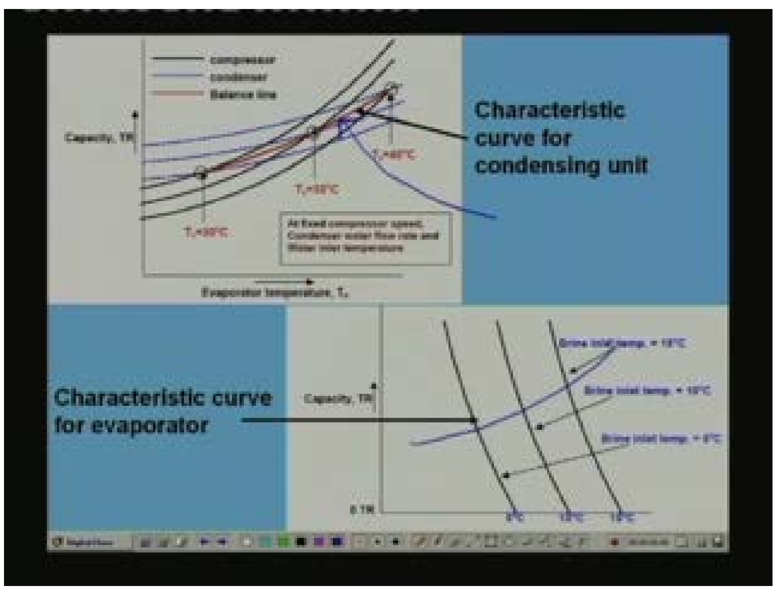

That means this red line okay. As I said this is the curve for the condensing unit so this curve is super imposed onto this one okay.

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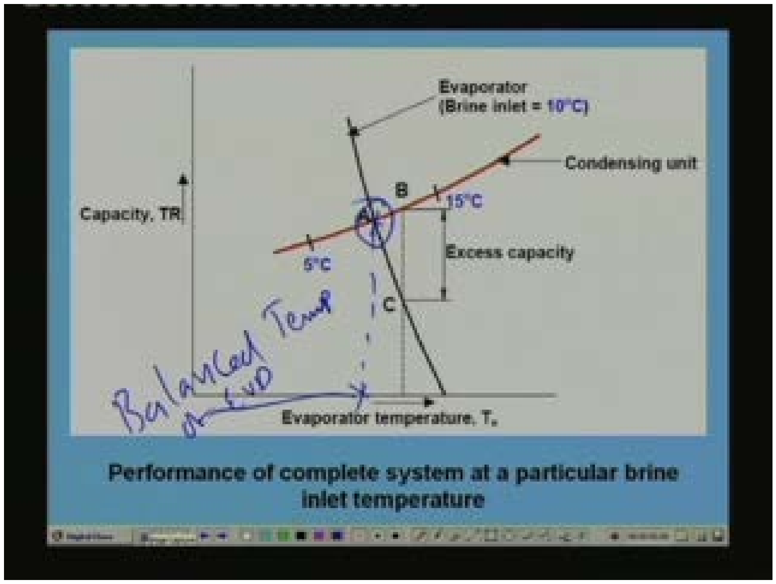

And where these two curve intersects that is this point, this will give the balance point for the entire system okay. And at this point you will find that the evaporator temperature is this. So this is the balanced temperature of evaporator okay.

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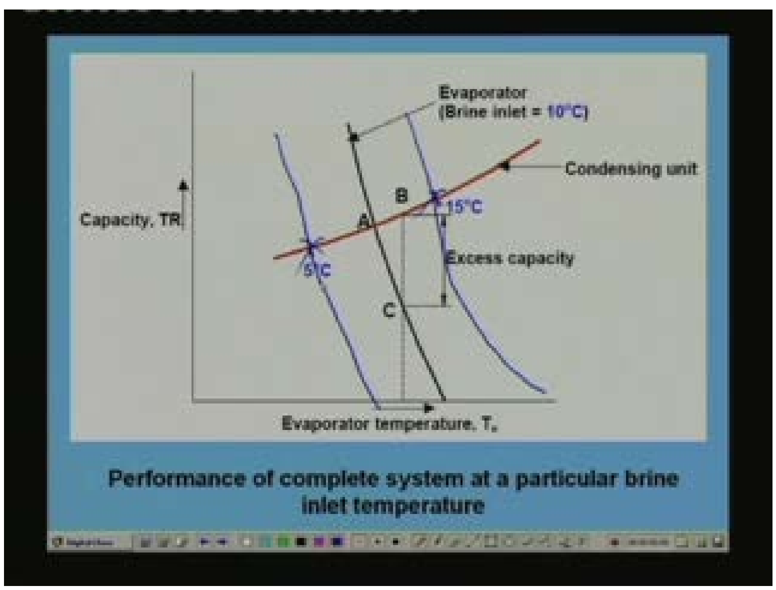

And suppose if it is, if the brine inlet temperature is not the ten degrees. But if it is fifteen degree then you will have the curve like this. Because the fifteen degree curve is here if it is five degree you will have another curve like this okay. So you have different brine inlet temperatures and again you can get the different balance points.

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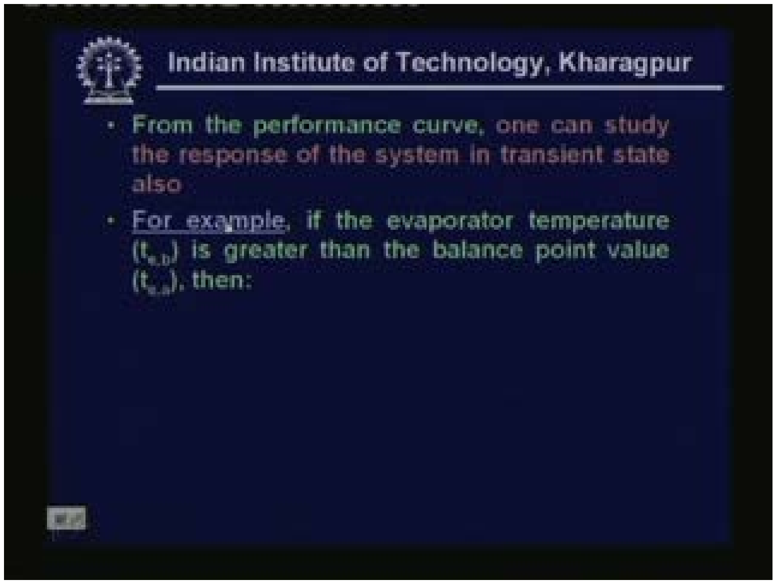

From the performance curve one can study the response of the system in transient state also okay.

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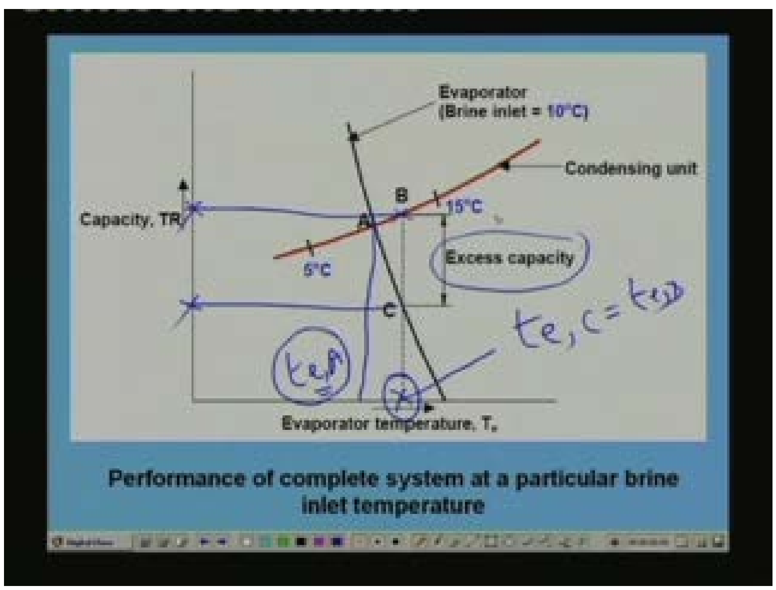

For example, as I said let this is the balance point and at this balance point let us say that teA is the evaporator temperature at balance point okay. And let us say that due to some reason now system is in a transient state and at this transient state this is the evaporator temperature okay.

So to start with let us say that we have a evaporator temperature teC is equal to teB. Now there is no balance between condensing unit and evaporator. Because you can see that the condensing unit the capacity is this where as the evaporator the capacity is this okay.

That means the condensing unit has much higher capacity compared to the evaporator okay. And the difference between these two is the excess capacity okay. So when the condenser has an excess capacity what happens? When the condenser has excess capacity since the size of the condense is fixed it can condense more mass flow rate or what it can do is it for the given mass flow rate it can condensation can take place at lower condenser temperatures okay. That means your condenser temperature Tc will be reduced.

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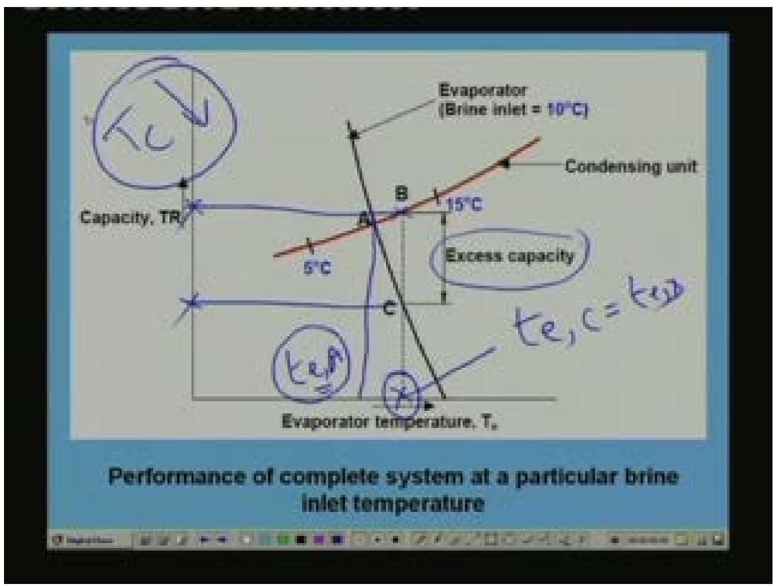

Okay, once Tc reduces one the condenser temperature reduces evaporator temperature also reduces okay. Once the evaporator temperature reduces the balance point will shift now from the unsteady value of Tca teC to the steady value of teB okay.

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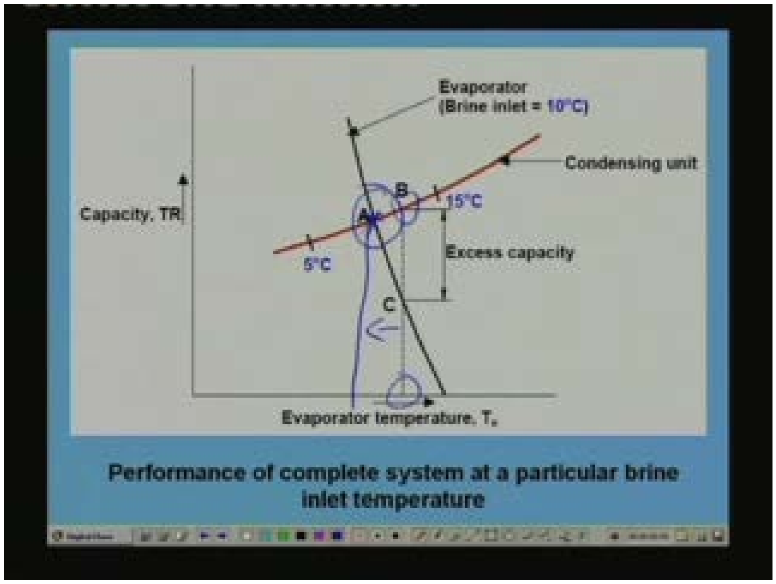

That means to start with it at the, this point because the excess capacity condenser temperature reduces. Once the condenser temperature reduces evaporator temperature also reduces. So the point moves in this direction okay. And when it reaches this point both the capacities are matched and the system reaches a steady state okay. So this kind of very useful information can be obtained by this performance characteristics curves for the complete system.

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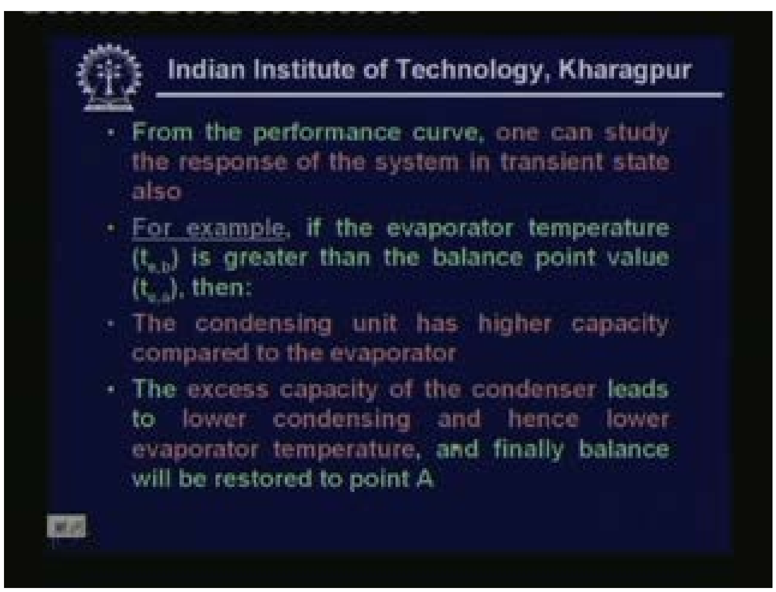

Okay, so this is what is I have already mentioned. The condensing unit has a higher capacity compared to the evaporator in the transient state. When the evaporator temperature is high the excess capacity of the condense leads to lower condensing and hence lower evaporator temperature and finally balance will be restored to point A.

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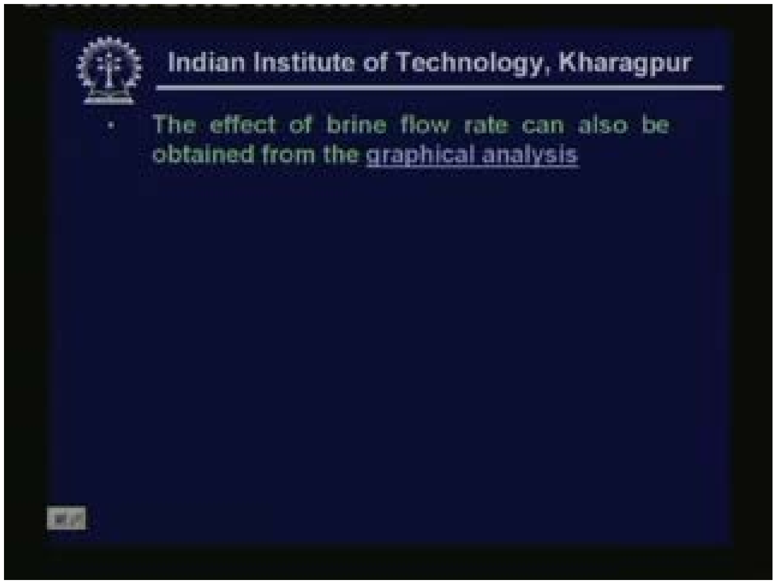

The effect of brine flow rate can also be obtained from the graphical analysis.

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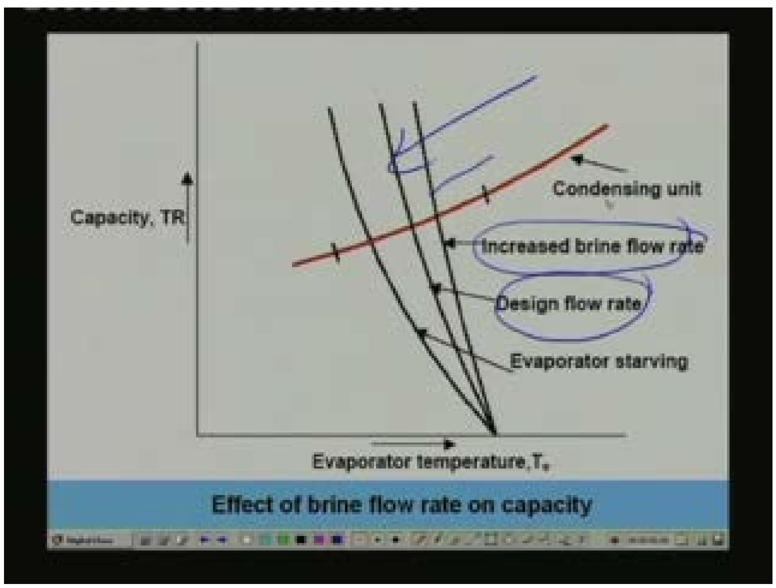

Okay, what happens let us say the, this is the design flow rate okay. So this is this curve is for the design flow rate now the flow rate increases okay. Let s say that this is the increase in flow rate curve okay. What happens to the capacity once the brine flow rate increases when you are keeping all other parameters constant and increasing teB brine flow rate the heat transfer coefficient on te brine side increases. Because your increasing the flow rate means you are increasing the velocity so heat transfer coefficient increases. Once the heat transfer coefficient increases over all capacity of the system increases okay. Now the system will be balance at a higher capacity right. So that is what has happened here.

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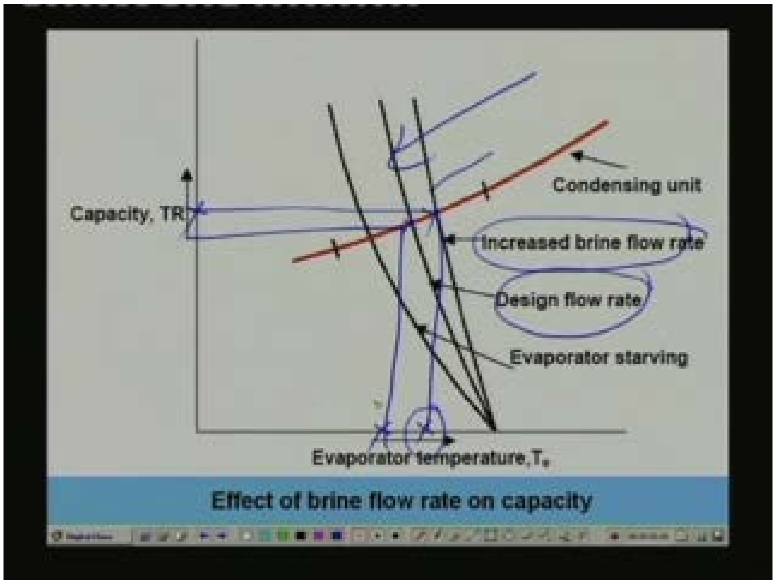

So if you have increased the capacity you can find that at this is the balance balanced design point capacity and at increased brine flow rate this is the capacity okay. But along with the capacity the temperature also increased okay. If this is the design temperature since the brine flow rate has increased the balance flow rate evaporator temperature also increased okay.

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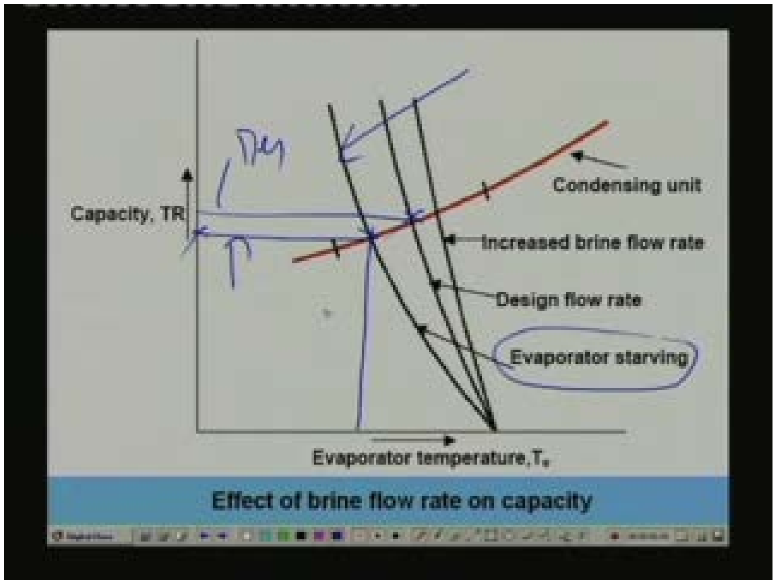

You can also see the opposing effect for example when you are reducing the brine flow rate okay. This is the curve for reduced brine flow rate when you reduce the brine flow rate heat transfer coefficient on the brine side increases, over all heat transfer coefficient increases, evaporator temperature increases, capacity also increases okay. Capacity also decrease I am sorry when the flow rate decreases the evaporator temperature decreases and capacity also decreases. Compared to the design point, this is the design point, this is at the reduced flow rate okay. And at this flow rate you, it is said that the evaporator is said to be starving okay. So that means the evaporator is in starving condition when the flow rate is reduced okay.

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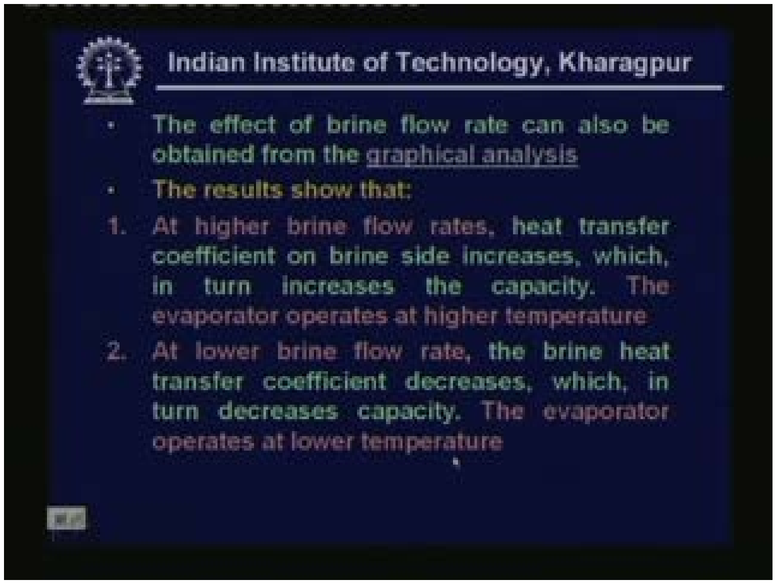

So what is summarized here the result show that at higher brine flow rate s heat transfer coefficient on brine side increases which in turn increases the capacity the evaporator operates at higher temperature. And at lower brine flow rate the brine heat transfer coefficient decreases which in turn decreases capacity the evaporator operates at lower temperate and you all them you call that state as the state of starving.

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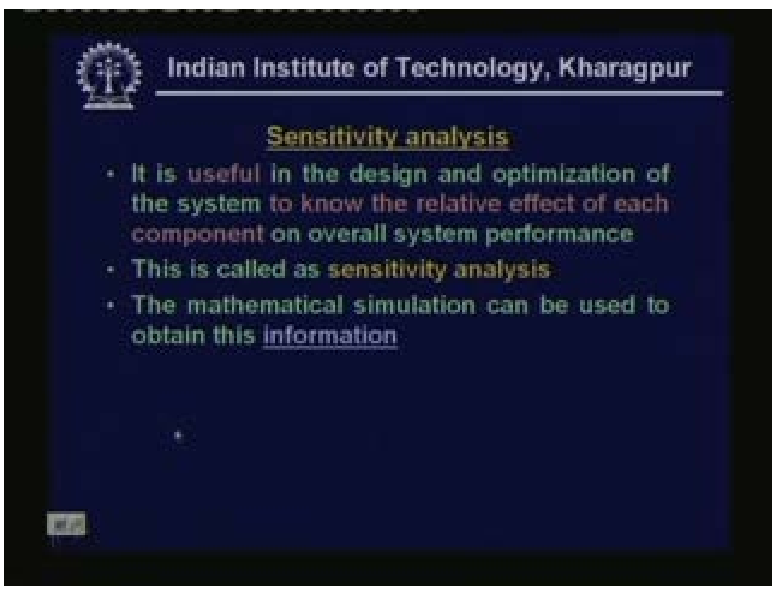

An important aspect when you are doing the complete system analysis is what is known as the sensitivity analysis. What is sensitivity analysis and what is its use? This analysis is useful in the design and optimization of the system. And what does it tell us what is the relative effect of each component on overall system performance okay. This kind of analysis is called as sensitivity analysis. The mathematical simulation can be used to obtain the information okay, I will, example this is taken from ha te book of Stoecker and Jones.

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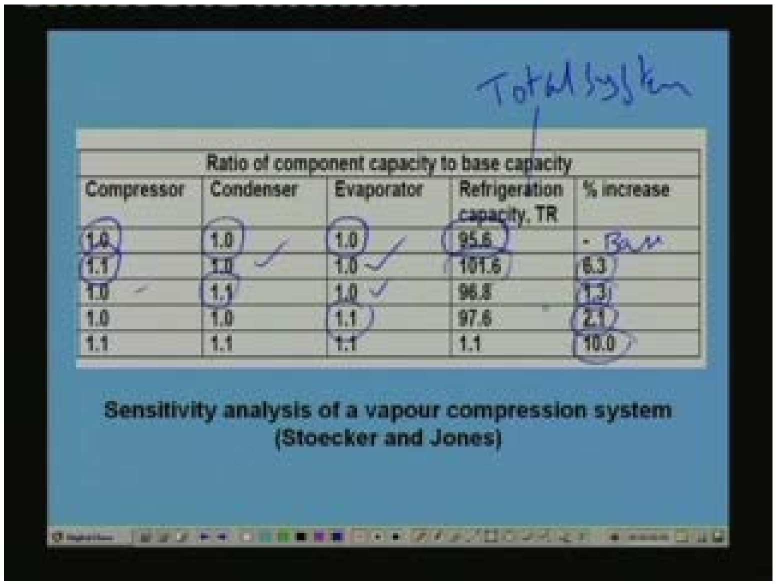

This gives the sensitivity analysis of the vapor compression system at a fixed condenser and fixed evaporator and ambient temperatures. What is done here is, this is the base case okay. Where you have a compressor, let us say that the compressor capacity is one and you have a condenser capacity is one and evaporator has a capacity of one so it has a, this is the base case okay. At this base case it is observed from the calculation that the refrigerant capacity is ninety five point six tones of six tones okay. Now what is done here is all other parameters are kept constant.

That means the condenser is kept constant no change is made in the condenser. No change is made in te evaporator only the compressor capacity is increased by ten percent okay. That means it becomes from one to one point one when the compressor capacity is increased by ten percent you find that refrigerant capacity of the overall refrigerant capacity okay. So this is the total system okay. Total system capacity increases by six point three percent okay. Now the second step what is done is compressor is kept same evaporator is kept same. But the condenser temperature is increased by ten percent. When the condenser temperature is increased by ten percent you find that the total system capacity increases by only one point three percent okay.

Next the effect of evaporator is studied by keeping compressor and condenser constant but by increasing the evaporator capacity okay, by ten percent when you increase the evaporator capacity by ten percent you find that the refrigerant capacity increases by two point one percent okay.

Now when you increase everything by ten percent obviously the total capacity also increases by ten percent okay. So this is, this kind of information you can get from the sensitivity analysis what is the use of this kind of information or this kind of data. This data clearly shows that if you have to invest money, it is better that you invest money on the compressor. Because at ten percent variation compressor is giving rise to six point three increase in the total capacity of the system. Whereas the ten percent rise in the condenser is giving only a one point three percent increase in the capacity okay.

That means in terms of relative influence compressor have the most influence okay. Next to compressor evaporator is has the highest influence next to that condenser has the highest influence okay.

So you know where to do the improvement or where to invest. So that you can get the maximum possible benefit this is the advantage of sensitivity analysis okay. Of course the sensitivity analysis of an actual system can be quite complicated because in actual system consists of several other components. And several other factors have got to be considered okay. But this example just shows the basic concept and basic use of this kind of a analysis okay.

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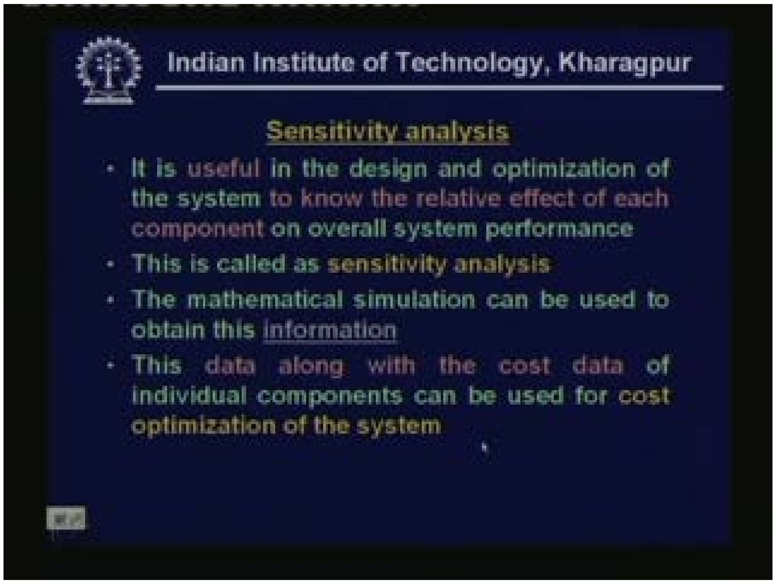

This data along with the cost data of individual components can be used for cost optimization of the system okay, is this is very useful. So with this I complete the analysis of the complete vapor comprant system. As once again let me repeat that whatever we have discussed today is very brief and it is only just to give an idea of how a system analysis a complete system analysis is done by using either graphical methods or mathematical methods okay. You can refer to more advanced books or journals for more information on this kind of system analysis okay. Let me summarize what we have learnt in this lesson. In this lecture a brief introduction is given on analysis of complete vapor compression system principle of graphical and mathematical methods are discussed briefly and the concept is illustrated with a simple example taking cooled condenser and brine chiller okay. So at this point I stop the, this lecture.

Thank you.