Refrigeration and Air Conditioning
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Lecture No. # 21
Refrigeration System Components:
Compressor (contd.)

Welcome back in the last lecture. I introduced refrigerant compressors then I explained an ideal reciprocating compressor without clearance and with clearance. In this lecture I shall explain the effect of operating temperatures.

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On the performance of an ideal reciprocating compressor with clearance then I shall explain the differences between an actual compressor and an ideal compressor.

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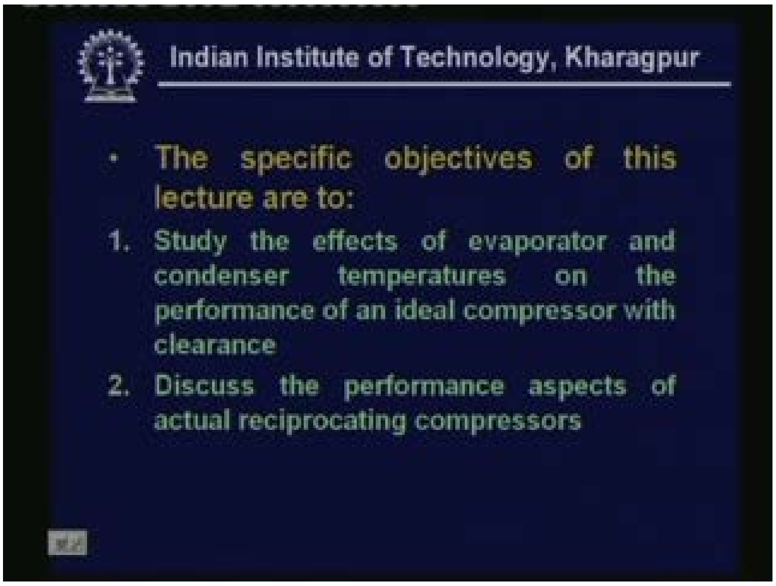

So the specific objectives of this particular lesson are to study the effects of evaporator and condenser temperatures on the performance of an ideal compressor with clearance and then to discuss the performance aspects of actual reciprocating compressors.

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At the end of this lesson you should be able to explain the effects of evaporator and condenser temperatures on compressor performance and practical issues and list the differences between an ideal and actual compressor and explain the procedure for evaluating the performance of actual compressors.

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So let us look at the performance aspects of an ideal compressor with clearance. First let us look at the effect of evaporator temperature. The effect of evaporator temperature is obtained by keeping the condenser temperature or pressure constant and also keeping the compressor displacement and clearance ratio fixed. That means we are finding out the effects by keeping these parameters as fixed and to simply the discussions. It is further assumed that the refrigeration cycle is a saturated single stage saturated standard cycle.

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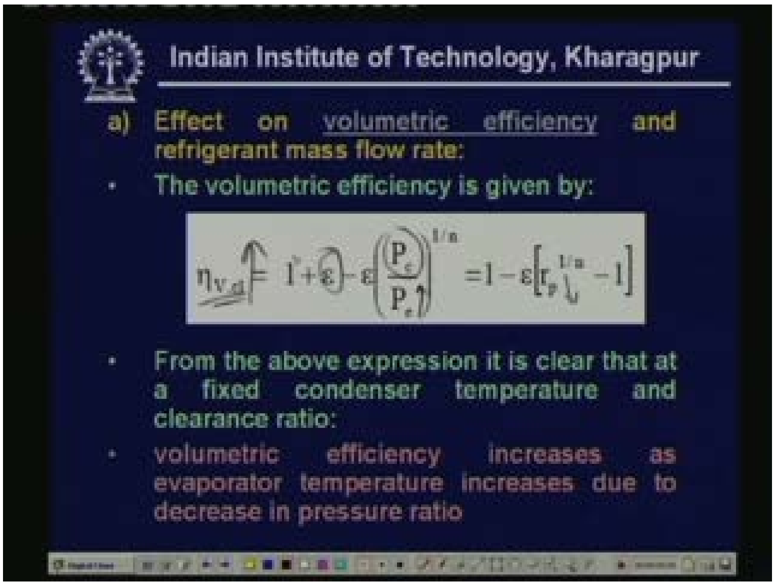

First let us look at the effect of evaporator temperature on volumetric efficiency and refrigerant mass flow rate. As you have seen in the last class the volumetric efficiency is given by this expression clearance volumetric efficiency is equal to one plus epsilon minus epsilon into Pc by Pe to the power of one by n. And as I have explained we are finding the performance by keeping this parameter fixed. That means the clearance ratio fixed and we are also keeping the condenser temperature or pressure fixed. And then we are varying the evaporator temperature varying the evaporator temperature is equivalent to varying the evaporator pressure. So from this expression you can see that as you are increasing the evaporator pressure. That means as you increase Pe the pressure ratio reduces once the pressure ratio reduces the volumetric efficiency increases. So this is very clear from this figure from this equation. This I, as the same thing can also be seen from this figure.

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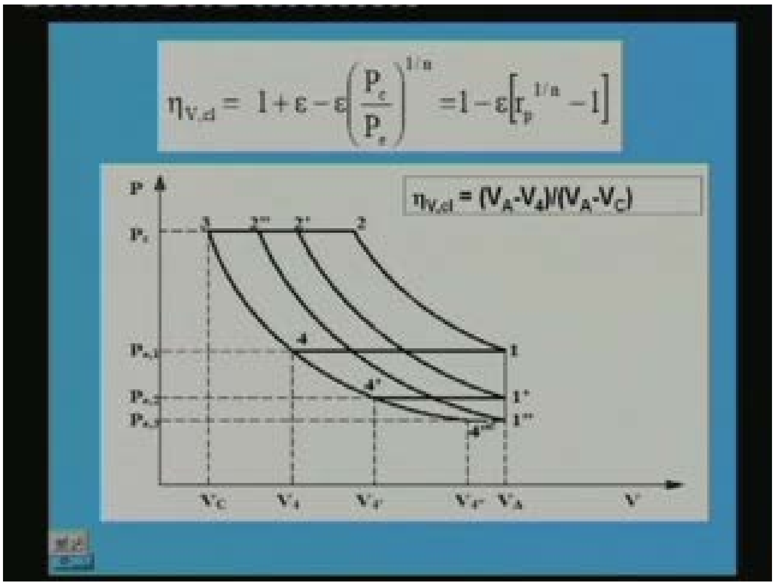

Okay, so it is very clear from this figure what we have here is a P-V diagram of a compressor with clearance and here we are varying the evaporatic pressures okay. As I said varying the evaporator pressure is equivalent to varying the evaporator temperature. For example look at this evaporator pressure at an evaporator pressure.

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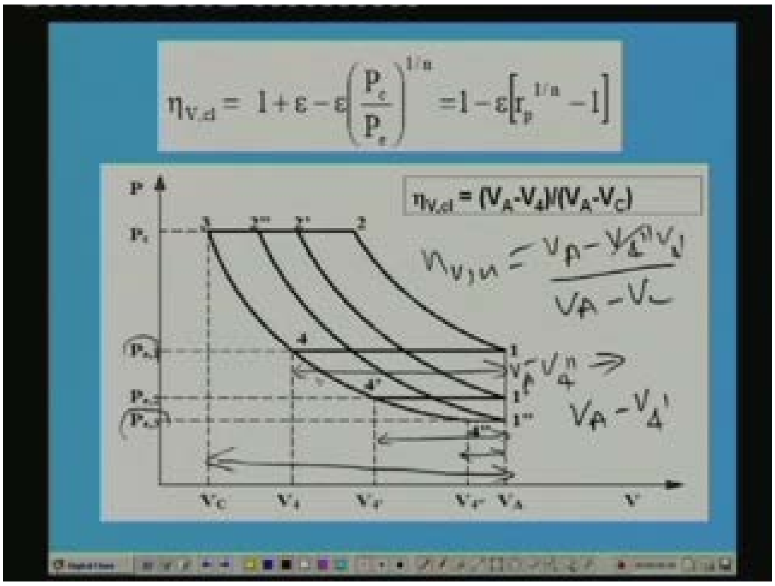

For example let Pe three this is the actual volume compressed and this is the displacement of the compressor. That means for this pressure the volumetric efficiency as given from this equation is simply equal to VA minus V four dash divided by VA minus VC. So now as you increase this evaporator pressure from Pe three to Pe two you see that the volume of refrigerant compressed has increased from V one double dash that is VA minus V four double dash to VA minus V four dash okay. And as a result this will become V four dash okay. So the volumetric efficiency increased and further increase in evaporator pressure has increase the volumetric efficiency further. Because volume of the refrigerant compressed has increased.

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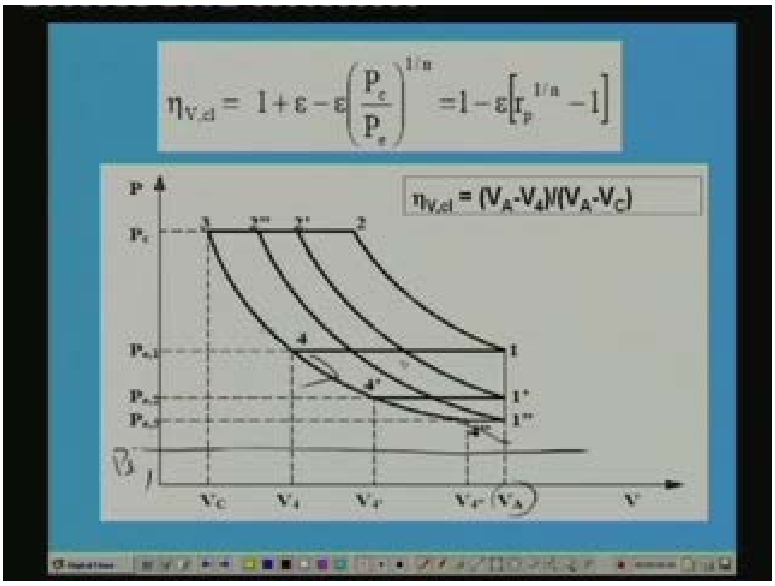

And from this you can see that for example when you are reducing the evaporator pressure further. Let us say that we are reducing the evaporator further a point will come at which this line will simply meet the point VA okay. That means the amount of refrigerant compressed will be zero. That means this is the limiting evaporator pressure at which the volumetric efficiency becomes zero. That means it will be simply re-expanding and compressing along the same line okay. The same thing is explained here also.

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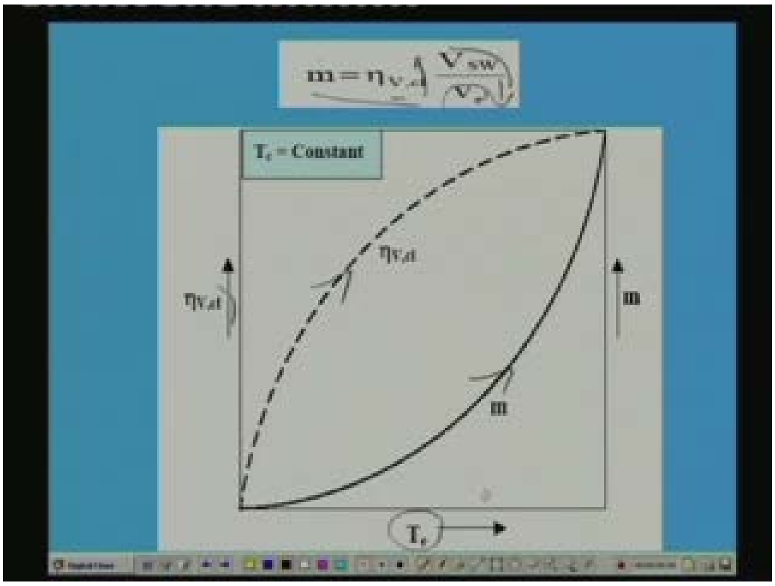

You can see that here we are varying the evaporator temperature or pressure and we are seeing the effect of this on clearance volumetric efficiency. So you can see that the clearance volumetric efficiency increases rapidly as evaporator temperature increases. Now what is the effect of this evaporator temperature on mass flow rate. We know that the mass flow rate of the compressor with clearance is given by this expression where this is the clearance volumetric efficiency V dot sw is the swept volume rate of the compressor which is fixed and Ve is the specific volume at the inlet to the compressor. So as you are increasing the evaporator temperature two things take place first is the volumetric efficiency in increases as shown here. And this specific volume Ve reduces okay. So you can see that in the numerator is increasing and denominator is reducing as a result mass flow rate of the refrigerant increases very rapidly as the evaporator temperature increases.

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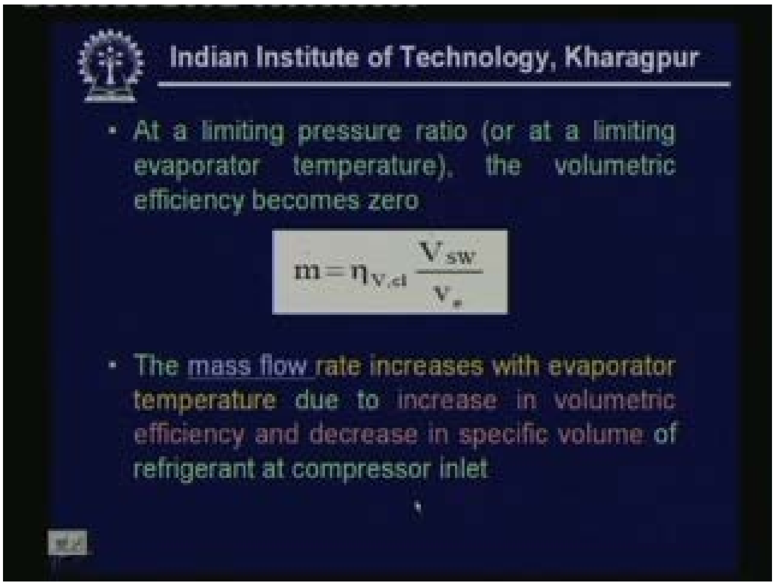

So as I have told at a limiting pressure ratio or at a limiting evaporator temperature the volumetric efficiency becomes zero okay. And the mass flow rate as I have already explained is equal to the product of volumetric efficiency into swept volume rate divided by the specific volume. And the mass flow rate increases with evaporator temperature due to increase in volumetric efficiency and decrease in specific volume of refrigerant at compressor inlet this is very clear from the figure.

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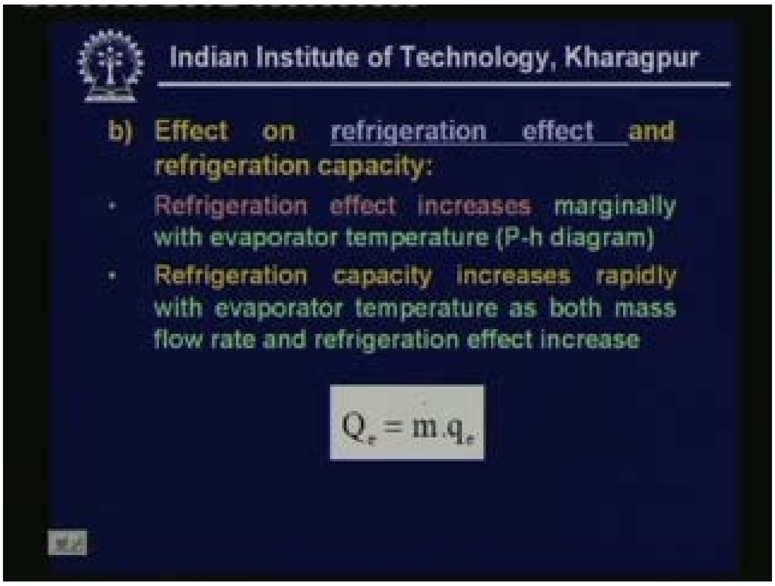

Now let us look at the effect of evaporator temperature on refrigeration effect and refrigeration capacity when I say the effect of evaporator temperature on the refrigerant capacity of a compressor. What exactly we mean a compressor cannot provide a refrigeration capacity okay. So what we mean by refrigeration capacity of a compressor mean it is the refrigeration capacity of a system which uses this particular compressor. That means we are talking about the performance of a system which uses this compressor okay. So let us see the effect of the temperature on the refrigeration effect and capacity refrigeration effect increases marginally with evaporator temperature this will be clear from the P-h diagram okay. And refrigeration capacity increases rapidly with evaporator temperature. Because both mass flow rate and refrigeration effect increase with evaporator temperature okay. So let us look at the figure.

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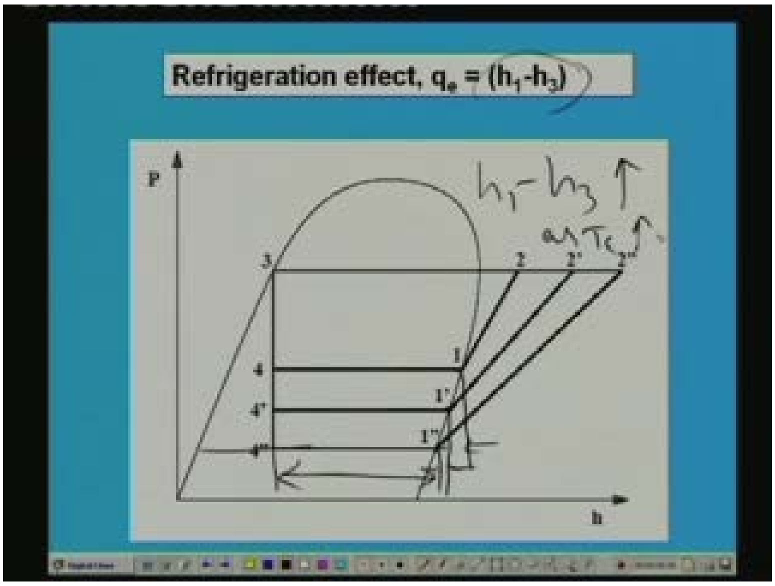

You can see here that at this evaporator temperature or evaporator pressure this is the refrigeration effect okay. And as the evaporator temperature has increase the refrigeration effect increase by this much amount and further increase has, have raise the refrigeration effect by this much amount okay. So the refrigeration effect has given by h one minus h three increases as Te increases this is because of the shape of the P-h diagram.

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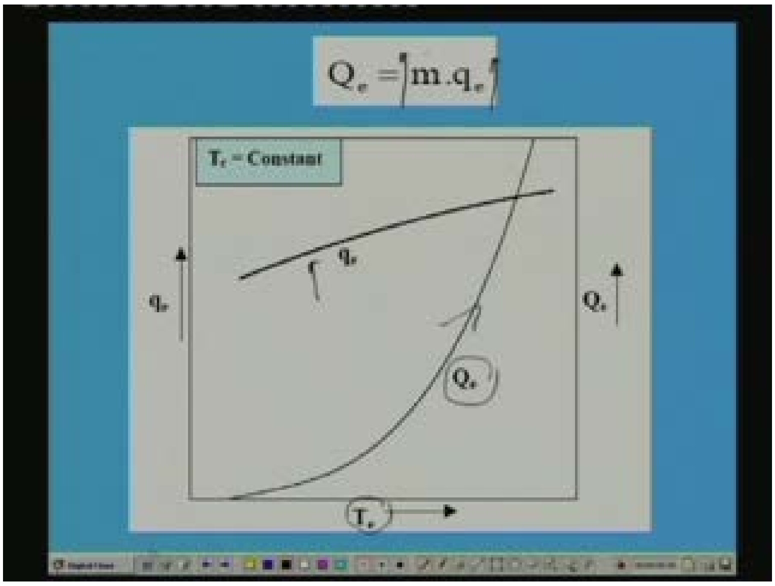

And the same thing is shown in this figure also as evaporator temperature is increasing the refrigeration effect here is increasing of course this increase is not very rapid because this depends upon the slope of the saturation vapour curve on P-h diagram okay. So this increase is not very rapid but the increase in refrigeration capacity is very rapid. Why is it? So because you can see that the refrigeration capacity is nothing but the product of mass flow rate in to refrigeration effect. So as temperature of evaporator is increasing both the mass flow rate as well as refrigeration effect both increase. Since both of them are increasing and the mass flow rate increases very rapidly the refrigeration capacity increases very rapidly with evaporator temperature.

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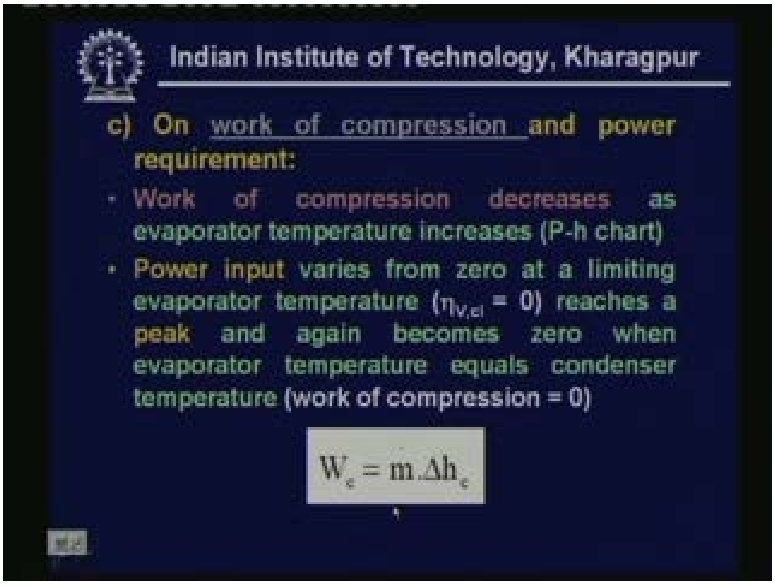

Now let us look at the effect of evaporator temperature on work of compression and power requirement work of compression decreases as evaporator temperature increases. This will be again clear from the P-h chart and power input varies from zero at a limiting evaporator temperature at which the clearance volumetric efficiency becomes zero. Then it reaches a peak and again it becomes zero when the evaporator temperature equals condenser temperature at this point the work of compression becomes zero okay. So finally the power input is a product of mass flow rate into delta hc. So when the evaporator temperature is very low mass flow rate becomes very low. And when the evaporator temperature is high work of compression becomes low. So as a result you have a peak okay. So this is clear from this figure.

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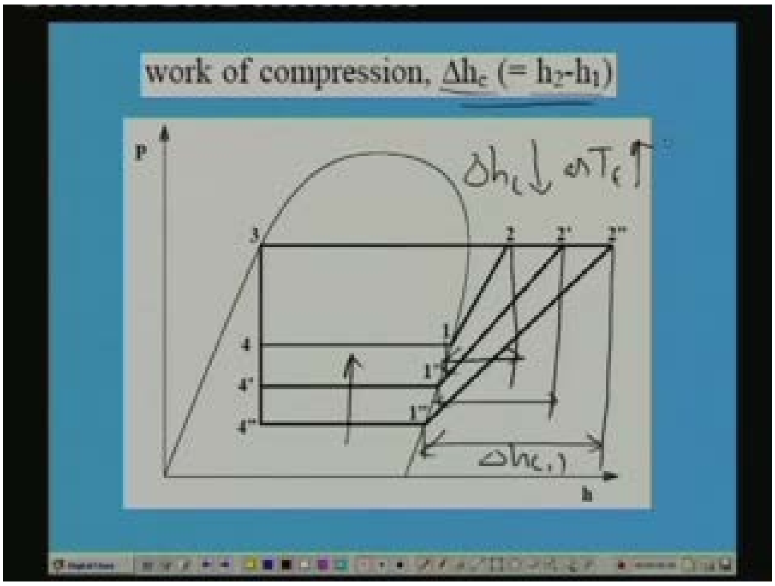

So here the work of compression delta hc is h two minus h one. So when the evaporator temperature is low this is the work of compression okay. So as evaporator temperature increased in this direction the work of compression is reduced. For example I have for this thing this is the work of compression and for this evaporator temperature. This is the work of compression. So delta hc as you can see is reducing as TE is increasing.

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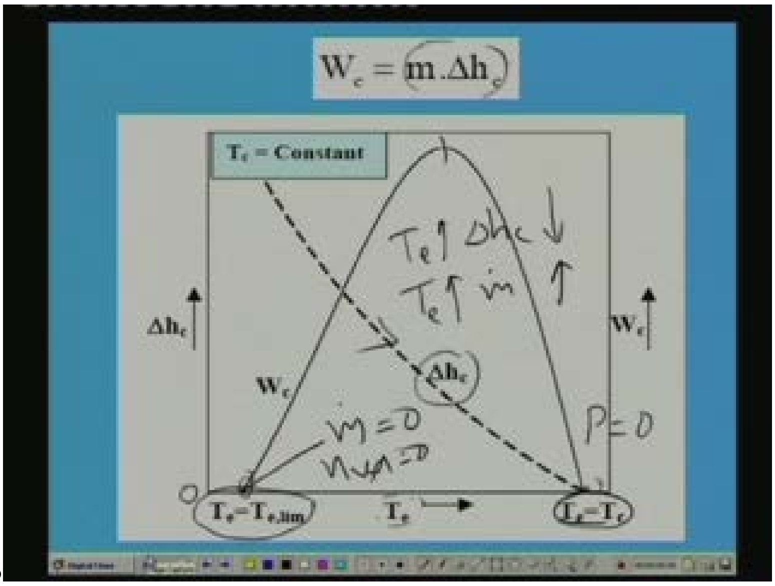

So same thing is shown in this figure you can see that work of compression is reducing as evaporator temperature is increasing okay. And at a limiting value when the evaporator temperature becomes equal to the condenser temperature the work of compression becomes zero okay. So this is the zero it becomes zero it becomes zero. So at at one side now let us look at the effect of evaporator temperature as I have already told in the power input to the compressor the power input to the compressor is given by mass flow rate into work of compression. And as we have seen as evaporator temperature increases work of compression is reducing okay. And we have also seen that as evaporator temperature increases mass flow rate increases okay.

So at a very low evaporator temperature. That means at a lower limit at this point the power input is zero because mass flow rate is equal to zero why the mass flow rate is equal to zero the mass flow rate is equal to zero. Because the clearance volumetric efficiency is zero okay. so at this point mass flow rate is zero. Since mass flow rate is zero obviously the power input is zero because power input is a product of mass flow rate into work of compression okay. So you can see that that is also zero and on the other end when the evaporator temperature becomes equal to the condenser temperature work of compression is equal to zero again power is equal to zero okay. That means the power curve starts from zero reaches a peak and again becomes zero okay. So this is the very important characteristic and we have to pay little attention to this okay. I will come to this in the next slide.

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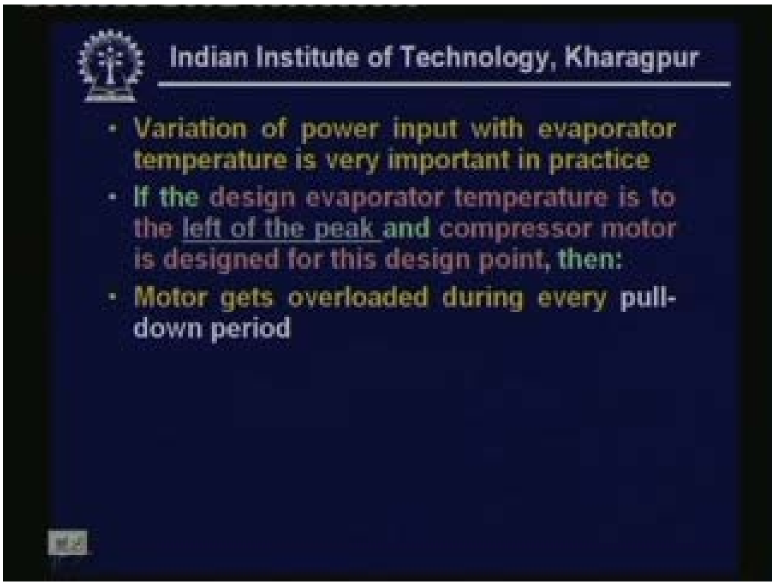

Variation of power input with evaporator temperature is very important in practice if the design evaporator temperature lies to the left of the peak and compressor motor is designed for this design point then a motor gets overloaded during every pull-down period. So what is the meaning of this?

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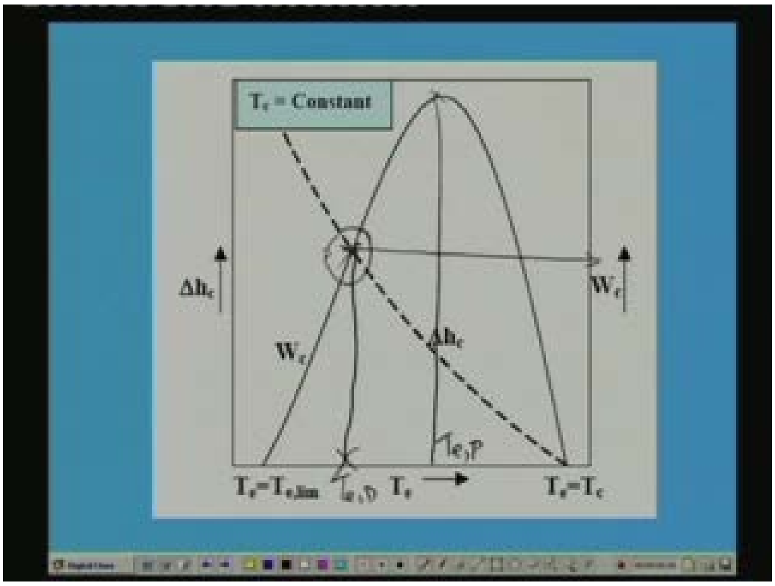

As you know this is the temperature at which the power becomes peak. Let us say that we are operating the system at this point. That means this is our design evaporator temperature okay. So at this design evaporator temperature what is the required power input required power input is this okay. So this is the required power input suppose you have selected a compressor motor for this design power input okay. It will work all right as long as the evaporator temperature is at this point but during pull-down what happens. First of all what do we mean by pull-down. So whenever refrigeration system is started initially the refrigeration system temperature will be same as that of the ambient. That means everything will be at the at an equilibrium condition and the temperature of all the parts all the components of the system will be same as the ambient temperature.

So when you start the refrigeration system for the first time the evaporator will be at ambient temperature condenser will be at ambient temperature okay. So as the system starts running refrigeration effect starts increasing and as a result the temperature of the system of the evaporator starts decreasing okay. So initially the evaporator temperature is same as the ambient temperature but with time the evaporator temperature reduces okay. This process continues till the required evaporator temperature is achieved in the refrigeration system.

Once the required evaporator temperature is achieved or once the required refrigeration space temperature is achieved some control action will take place and the required temperatures will be maintained. That means during every pull-down the evaporator temperature starts with high temperature may be equal be to the ambient temperature. And then it decreases and reaches the design point okay. So this is known as pull-down time and this is the pull-down process okay.

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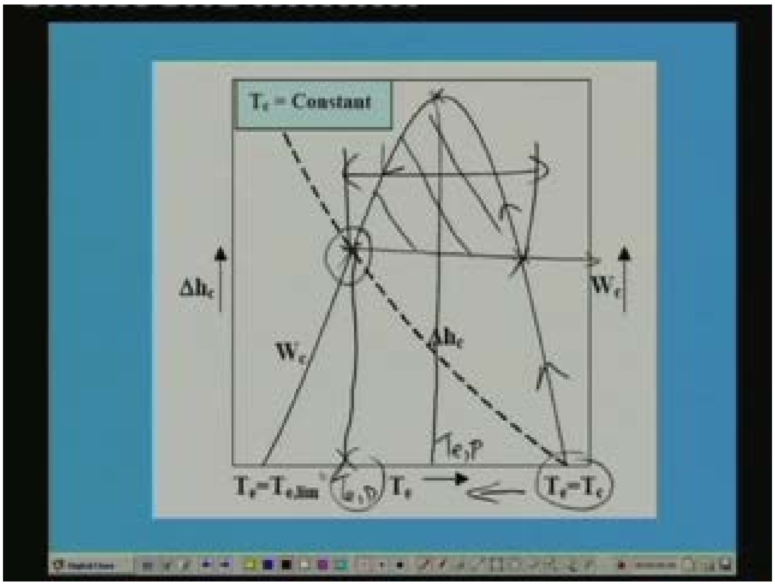

Now if you look at this power curve. Let us say that at the beginning of the pull-down the evaporator temperature is somewhere here okay. That means same as the condenser temperature which is equal to ambient temperature. So when the system is started the evaporator temperature starts decreasing in this direction when the evaporator temperature starts decreasing in this direction the power curve proceeds in this direction. Initially the power requirement is zero because the work of compression is zero okay. Even though the mass flow rate is quite high okay. So because the work of compression zero this is zero. So the power input increases like this and when it reaches at this point the power requirement at this point is same as the motor power rating okay. Because you have designed the motor for the design evaporator temperature okay. But the evaporator temperature has to decrease further when the evaporator temperature has to decrease further the power has to proceed along this line okay. Along this line and it has to reach the peak and then it has to decrease and then it has to come to the design point okay.

This happens during every pull-down. That means every during every pull-down between these two temperatures okay. The motor gets overloaded okay. And this is the amount of extra power required over and above the design power of the motor to bring the system from the initial temperature to the design temperature okay. If this happens during every pull-down then the motor will be continuously overloaded during every pull-down. And this may affect the life of the motor okay. So this is a very important problem.

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So what is the solution for his one easy solution is to design a motor for peak power okay. Of course this is not an efficient solution because most of the time the system has to operate at the design point. So when the system is operating at the design point the design power input will be much less than the peak power input. That means the compressor motor will be underutilized most of the time okay. This is not a very good solution. So what other solutions are possible one solution.

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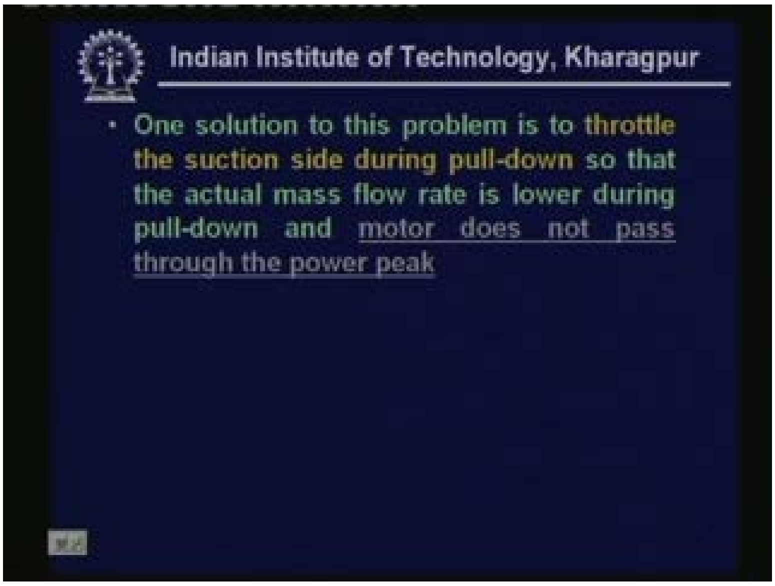

One practical solution is to throttle the suction side during pull-down. So that the actual mass flow rate is lower during the pull-down and motor does not pass through the power peak okay. So what is the meaning of this?

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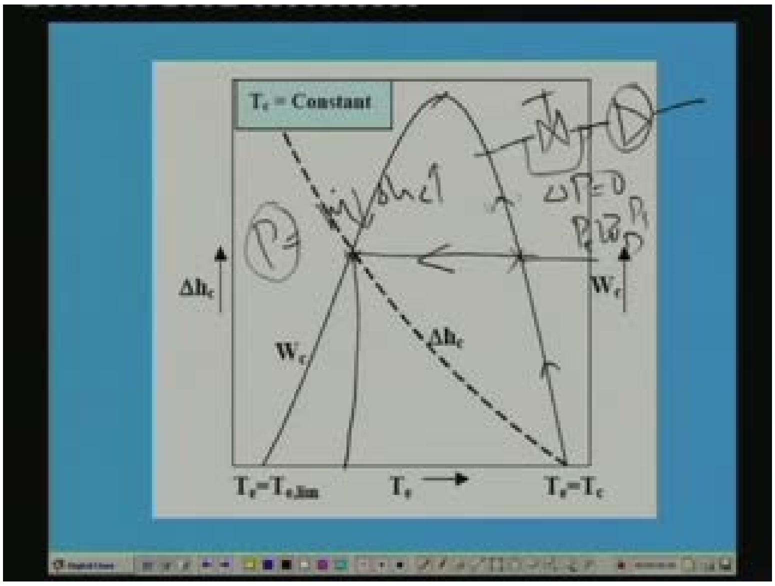

As I said this is the, let us say this is your design point and this is the design power okay, of the motor W design. So as soon as you start the refrigeration system. That means as soon as the pull-down process starts the power requirement starts increasing in this direction. So during this process what is done is there will be a valve at the inlet to the compressor. Let us say this is the compressor okay. And this valve is closed during the pull-down. So when this valve is closed there will be a large pressure drop across this valve okay. That means you are basically throttling the refrigerant vapour. So when you are introducing artificially a pressure drop across this the evaporator pressure will be much larger than the suction pressure as a result the mass flow rate of the refrigerant reduces okay. Once a mass flow rate reduces we know that power input is equal to mass flow rate into delta hc okay. So even though the delta hc is increasing since you are reducing the mass flow rate by throttling the power does not increase okay. This is increasing and mass flow rate is reducing.

So as a result instead of going through this power peak. Now the process will take place like this okay. That means you are skipping the peak right. So the required power input will be maintained in the design power input. So as soon as this reaches this point this valve is fully opened and this delta P becomes zero. So the system will work normally okay. So this is one of the practical solutions to the power peak problem.

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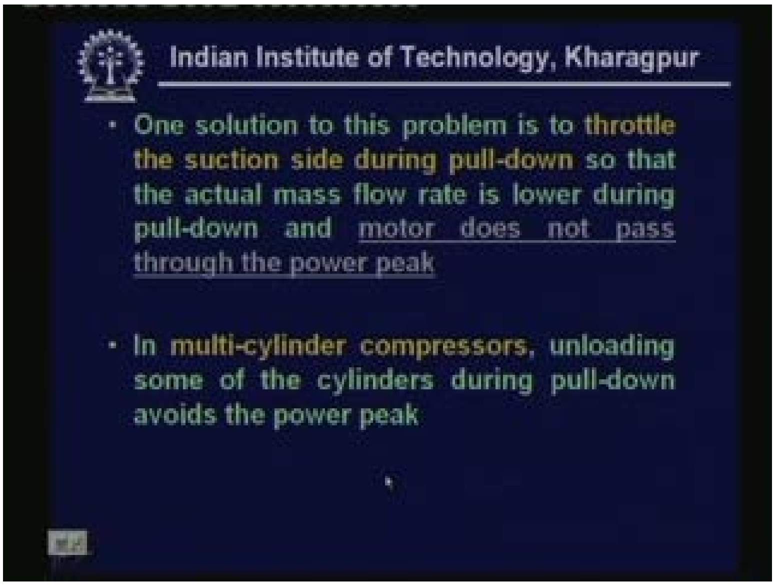

And of course it is also possible in multi-cylinder compressors to unload some of the cylinders during pull-down process when you are unloading some of the cylinders the total mass flow rate gets reduced okay. So since the total mass flow rate gets reduced the power requirement also reduces. So as soon as it reaches the design power design point then all the cylinders will be loaded otherwise some of the cylinders will be unloaded. So these are two practical solutions to take care of the power peak during pull-down.

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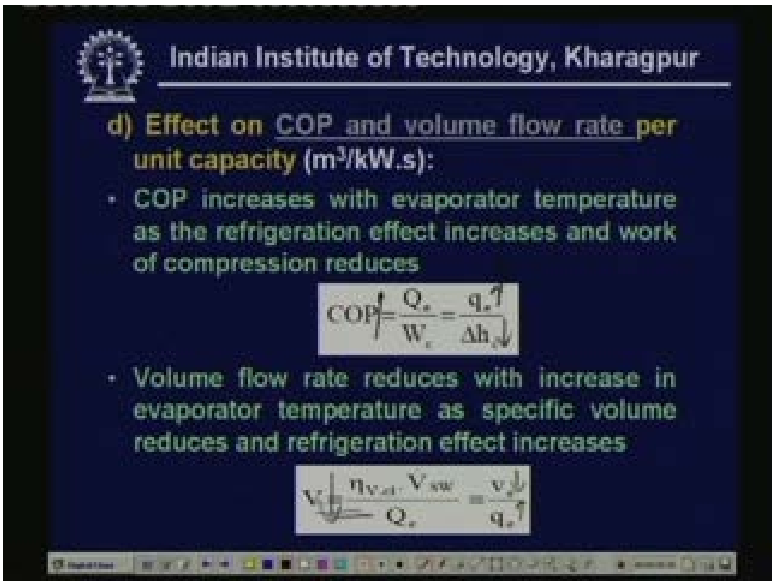

Now let us look at the effect of evaporator temperature on COP and volume flow rate per unit capacity. We know that COP is defined as the refrigerant capacity divided by the power input to the compressor that is Qe divided by Wc okay. So this can be written in terms of the refrigeration effect and work of compression. That means ultimately COP is equal to qe divided by delta hc where qe is the refrigeration effect and delta hc is the work of compression. And we have seen that as evaporator temperature increases refrigeration effect increases. That means this increases and delta hc reduces okay. Since refrigeration effect increases and delta hc reduces obviously COP increases with evaporator temperature okay. I will show you the figure. Now and next parameter is volume flow rate per unit capacity the volume flow rate per unit capacity is defined like this. So this can be written as specific volume divided by the refrigeration effect. So as evaporator temperature increases specific volume reduces and refrigeration effect increases as a result the volume flow rate per unit capacity reduces as evaporator temperature increases okay. So let me show this.

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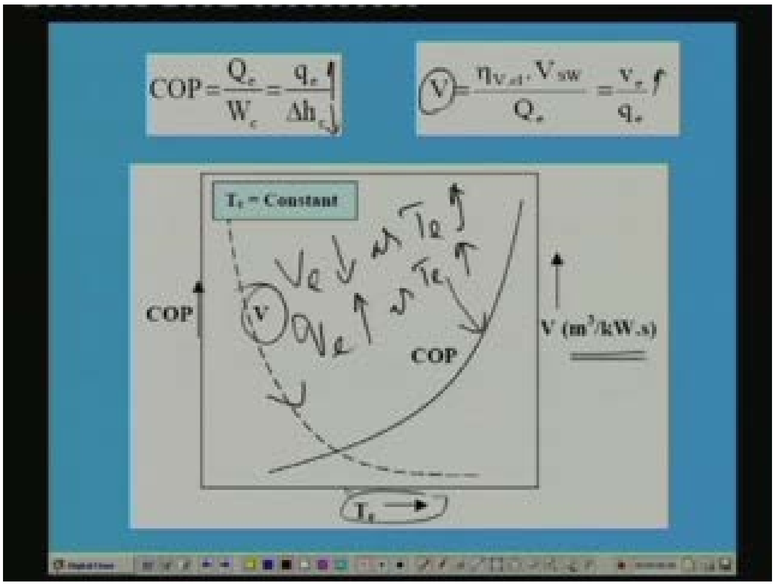

Okay so that is what is shown here this is the COP curve. So as I have already explained as evaporator temperature is increasing refrigeration effect increases and work of compression reduces. So you can see that COP increases quite rapidly as evaporator temperature is increasing this is the good thing and you get higher COP at higher evaporator temperatures. Of course this is in line with your performance of a reverse Carnot cycle and the second parameter is your volume flow rate per unit capacity that is in metre cube per kilo watt per second. So again as I have already this is equal to the ratio of specific volume Ve at compressor inlet divided by the refrigeration effect. So Ve reduces as Te increases and refrigeration effect increases as Te increases. As a result this volume flow rate per unit capacity reduces steeply with evaporator temperature.

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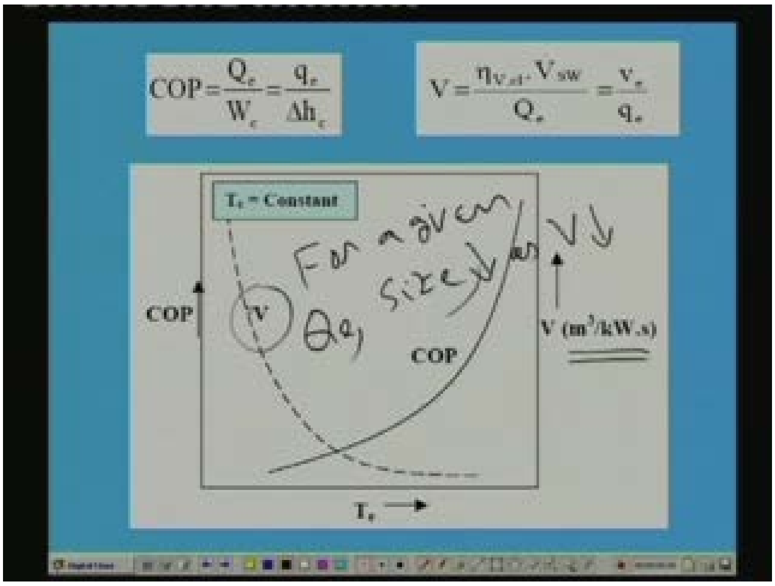

That means what is the Practical significance of this parameter. As you can see this is defined as metre cube per kilo watt per second. That means for a given capacity given refrigeration capacity. That means given Qe the size of the compressor reduces as V reduces okay. That means if you are operating the system at higher evaporator temperature the required size of the compressor reduces okay. So that is the practical significance.

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Now let us look at the effect of condensing temperature. So in most of the refrigerant systems atmospheric air is used as the heat sink and as we know the atmospheric temperature does not remain constant. In fact it can vary over a wide range that means the heat rejection temperature varies over a wide range depending upon the variation in the ambient temperature. That means the condensing temperature also varies okay. So variation condensing temperature obviously affects the performance of the compressor and also the refrigeration system.

So we need to study what is the effect of this on system performance. So this is done by keeping clearance ratio and evaporator temperature fixed. That means for studying the effect of the evaporator temperature what we have done is we have kept the clearance ratio and the condensing temperature fixed and then we varied the evaporator temperature okay. So to study the effect of the condensing temperature. We keep the evaporator temperature fixed and clearance ratio fixed and then vary the condensing temperature and find out what is its effect on mass flow rate volumetric efficiency and other performance parameters okay.

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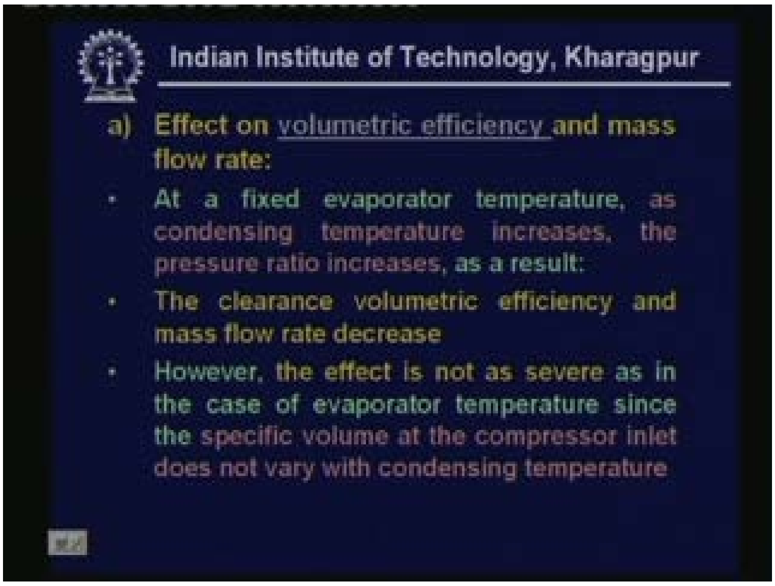

So first let us look at the effect of condensing temperature on volumetric efficiency and mass flow rate at a fixed evaporator temperature as condensing temperature increases the pressure ratio increases okay. So Pc Pc by Pe increases as Pc is increasing okay. As a result the clearance volumetric efficiency and mass flow rate decrease however the effect is not as severe as in the case of evaporator temperature. Since the specific volume at the compressor inlet does not vary with condensing temperature okay. That means higher condensing temperature affects the performance but not as adversely as low evaporator temperature affect to the performance okay. So let me show this on the figure.

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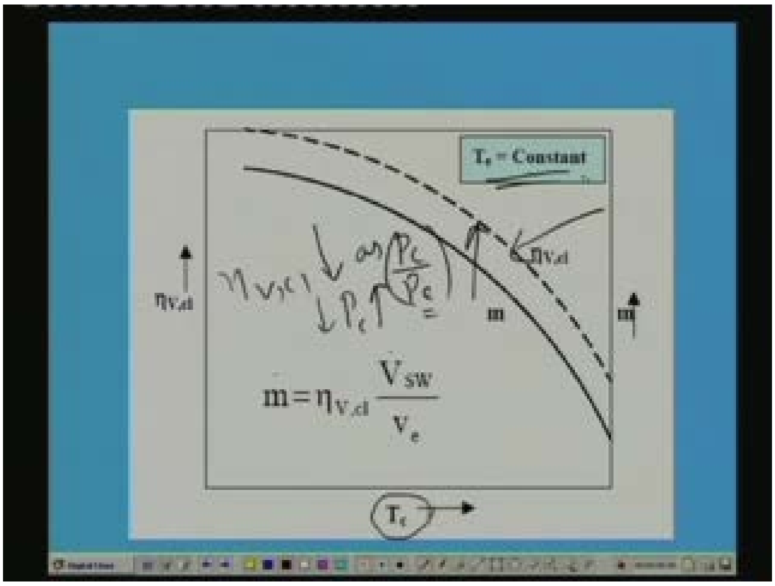

So as you know the volumetric efficiency clearance volumetric efficiency reduces as Pc by Pe increases okay. So we are fixing Pe that means this reduces as Pc increases okay. So that is what is shown here volumetric efficiency is reducing as condensing temperature is increasing for a fixed evaporator temperature.

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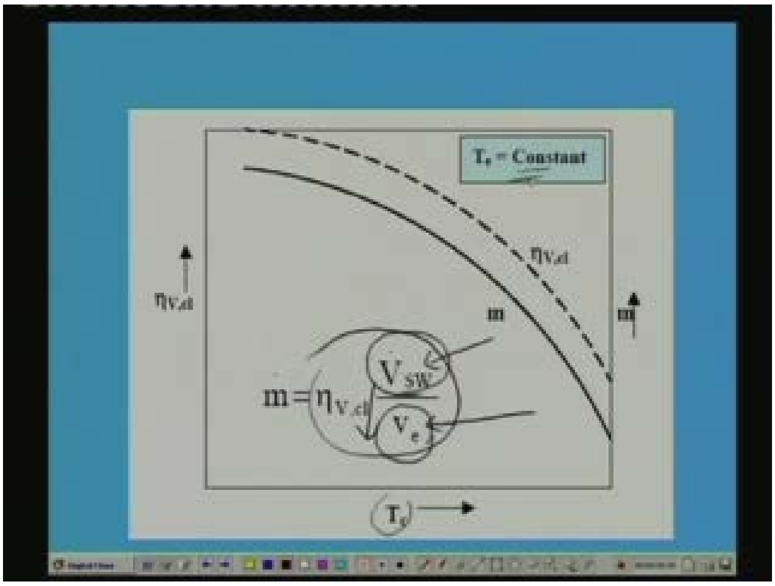

Okay and then the mass flow rate as you know is defined as the product of clearance volumetric efficiency displacement rate of the compressor and specific volume at the inlet to the compressor. So as you are increasing the condensing temperature this is reducing okay. This is fixed because we are assuming that the compressor is fixed. So clearance volumetric efficiency is reducing how about the specific volume at the inlet to the compressor. This does not remain this does not vary because condensing temperature has no effect on this as long as you are keeping the evaporator temperature constant okay.

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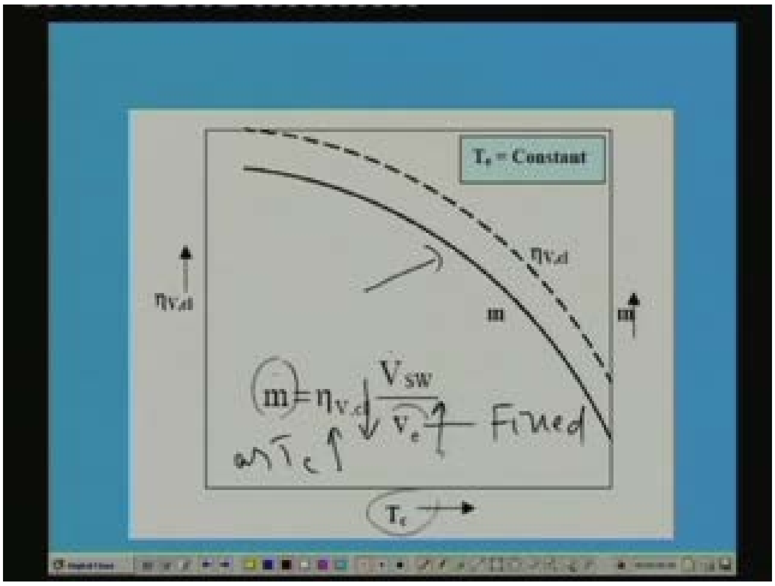

That means this is fixed and this is reducing as Tc is increasing. As a result the mass flow rate reduces with condensing temperature okay. But as you can see that the affect for a given delta T is not as severe as in the case of evaporator because in the in case of evaporator when you are reducing the evaporator temperature this is increasing okay and this is reducing. So you both numerator is reducing and denominator is increasing. So the effect on mass flow rate was much severe whereas here only the numerator reduces whereas the denominator remains constant.

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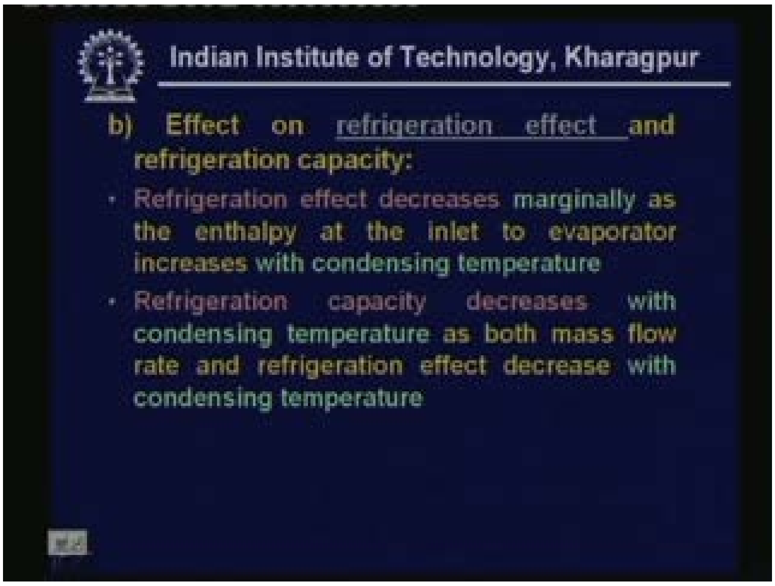

Now let us look at the effect of condensing temperature on refrigeration effect and refrigeration capacity refrigeration effect decreases marginally as the enthalpy at the inlet to evaporator increases with condensing temperature. I will show you this on P-h diagram and refrigeration capacity decreases with condensing temperature. Because both mass flow rate as well as refrigeration effect decrease with condensing temperature.

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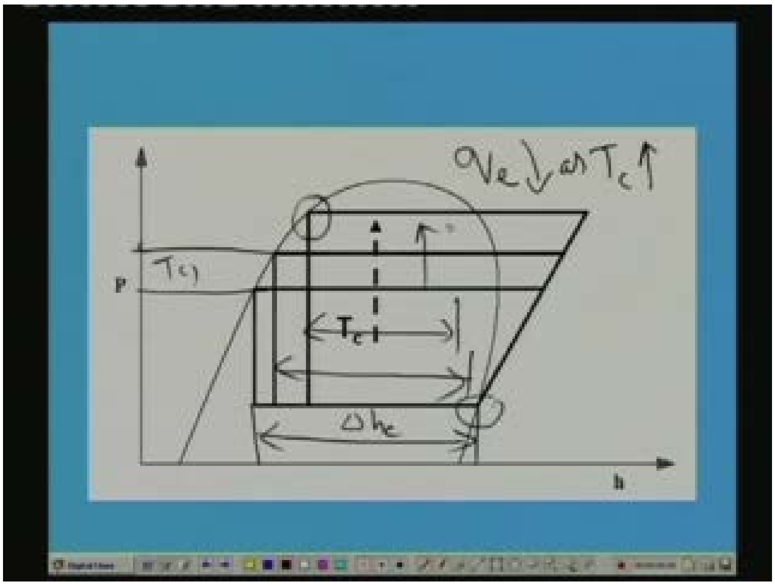

Okay so as I explained. So for a, let us say for this so for this condensing temperature let us say Tc one okay. So this is the refrigeration effect right and for this condensing temperature.

As you are increasing the condenser temperature the refrigeration effect is this. And if we increase it further the refrigeration effect becomes this okay. So as you can see refrigeration effect qe is reducing as Tc is increasing this point is fixed this is happening. Because the enthalpy at the inlet to the evaporator is increasing as you are increasing the pressure or the temperature okay.

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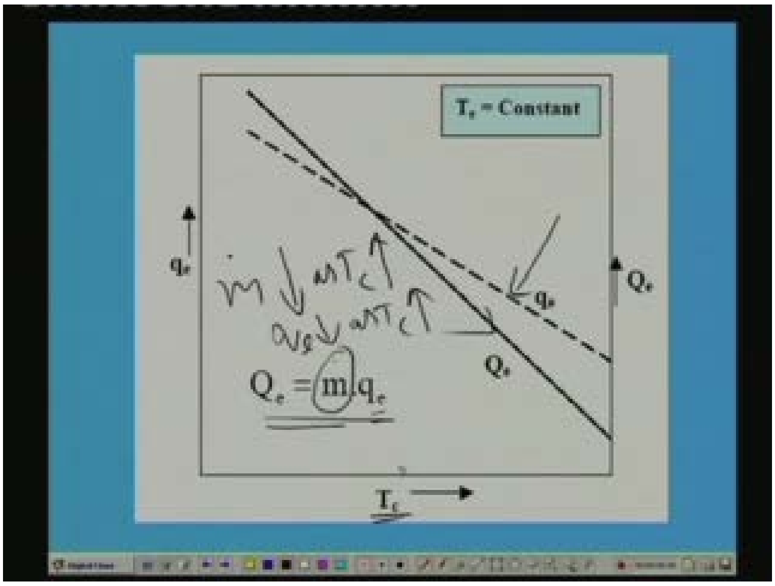

So as a result of which your refrigeration effect as seen here reduces with condensing temperature. Now what is the effect of the condensing temperature on refrigeration capacity. Refrigeration capacity is nothing but the product of mass flow rate into refrigeration effect. And we know that mass flow rate reduces as just now we have seen condensing temperature increases and here it is shown that qe also reduces as Tc increases okay. So both mass flow rate is also reducing and refrigeration effect is also reducing as condensing temperature is increased. So the refrigerant capacity reduces with condensing temperature.

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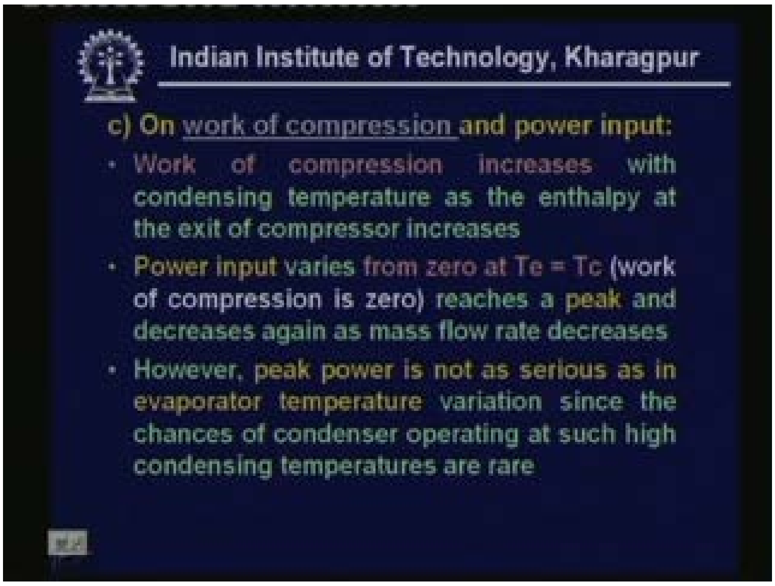

Now let us look at the effect of condensing temperature on work of compression. And power input work of compression increases with condensing temperature as the enthalpy at the exit of compressor increases. And power input varies from zero at Te is equal to Tc as we have seen earlier when evaporator temperature is same as condenser temperature the work of compression becomes zero okay. As the result the power input will be zero and then it reaches a peak as condenser temperature increases further and again decreases as the mass flow rate decreases okay. That means this performance shape of the curve will be almost similar to that of evaporator. However peak power is not as serious as in evaporator temperature variation since the chances of condenser operating at such high condensing temperatures are very rare okay. So let me explain this with the help of the P-h and P-h chart.

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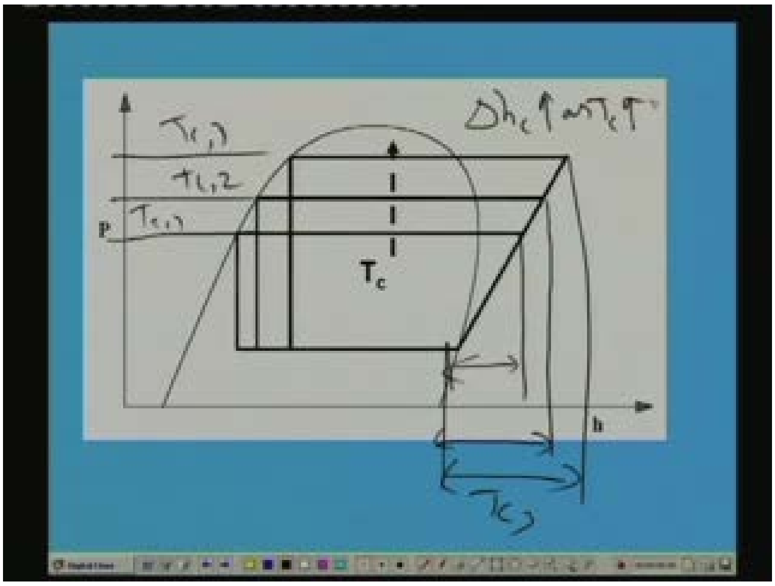

As you can see when the condensing temperature is Tc one. This is the work of compression as the condenser temperature becomes Tc two. This is the work of compression and this is the work of compression for Tc three okay. This is Tc three and this is Tc two. So as you can see that the work of compression increases as condenser temperature increases.

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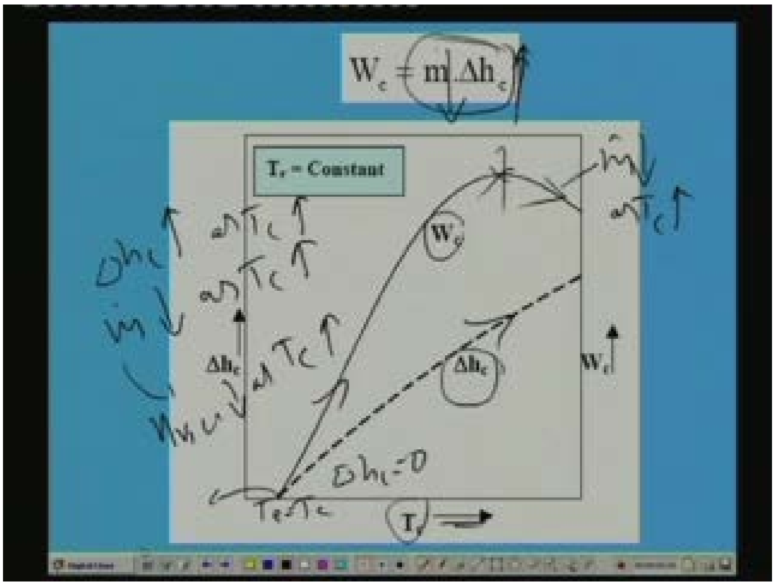

So that is what is shown in this figure the work of compression is increasing as condenser temperature is increasing. And as I have already explained the power input Wc is a product of mass flow rate of refrigerant into work of compression and work of compression is increasing monotonically that means delta hc increases as Tc increases. However mass flow rate reduces as Tc increases why does it reduce because your volumetric efficiency reduces as Tc increases okay. So you have opposing effects here mass flow rate is reducing and work of compression is increasing and at the limiting value. When Te is equal to Tc or Tc is equal to Te at this point work of compression is equal to zero okay. So the power input is zero and this power input increases because the work of compression is increasing it reaches a peak and then again it starts decreasing. Its starts decreasing because from this point onwards the effect of condensing temperature on mass flow rate is much higher than its effect on the work of compression okay. So this reduction takes place because mass flow rate reduces as condensing temperature increases okay.

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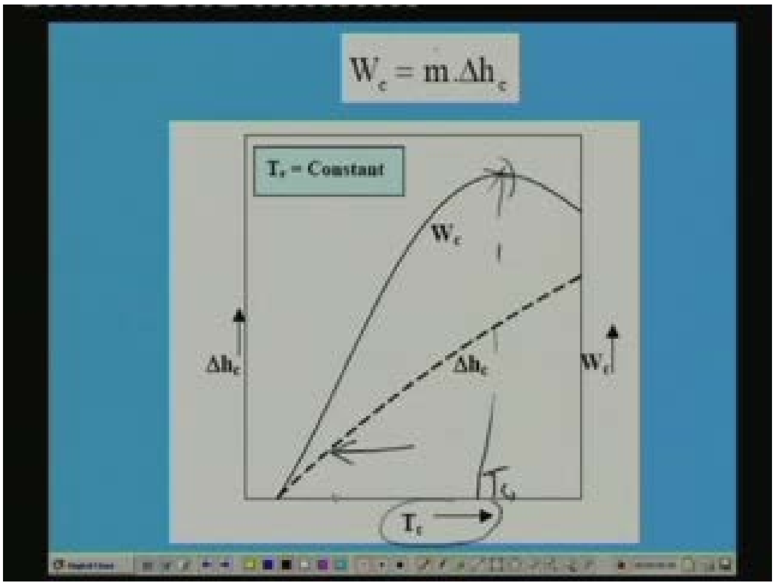

So you can see that here also we have a peak just like the power peak with evaporator temperature. However this problem is not very serious because this peak occurs normally at very high condenser temperatures okay. Most of the times we will be operating the condenser on this side only that means to the left of the peak. So the chances of compressor power reaching a peak due to variation in condensing temperature is not very I mean its remote that is what is mentioned here the peak power okay.

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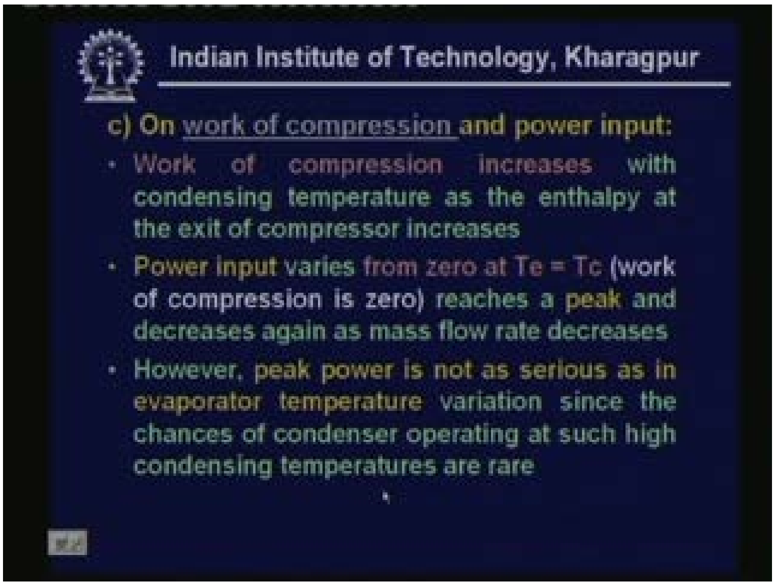

Effect of condensing temperature on peak power is not very serious.

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Now let us look at the effect of condensing temperature on COP and volume flow rate per unit capacity. So you can easily state this that the COP decreases with increase in condensing temperature because COP is the ratio of refrigeration effect and work of compression. So when you are increasing the condensing temperature refrigeration effect reduces and work of compression increases. That means the numerator reduces and denominator increases. So obviously COP will decrease okay. And what is the effect of volume flow rate the volume flow rate per unit capacity increases. Because as you are increasing the condensing temperature the specific the refrigeration effect decreases even the specific volume remains constant okay. So as a result the volume flow rate per unit capacity increases. Let me show this the figure.

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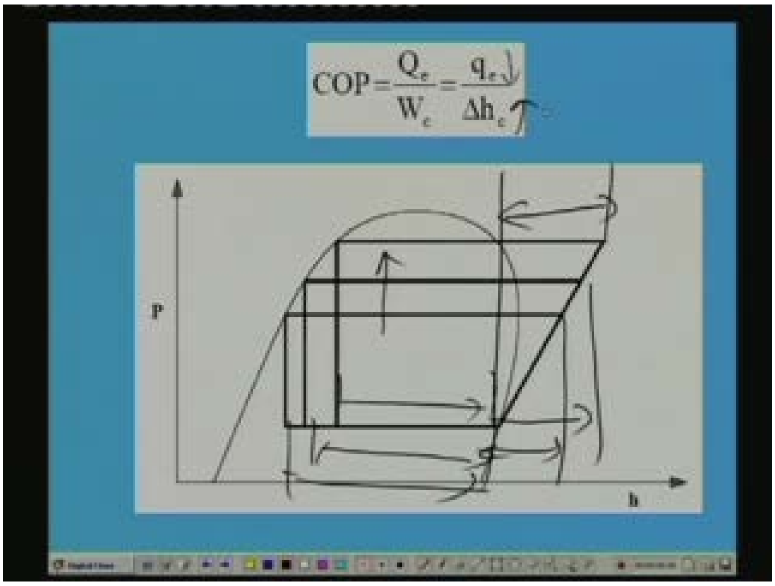

As you have seen in case of COP this is reducing as you are increasing the condensing temperature. The, you can see that initially it was this then it reduced to this much then it reduced to this much okay. That means the numerator is continuously reducing the refrigeration effect and the denominator as you have seen is increasing okay. From this point and then finally it is increases gone up to this value okay.

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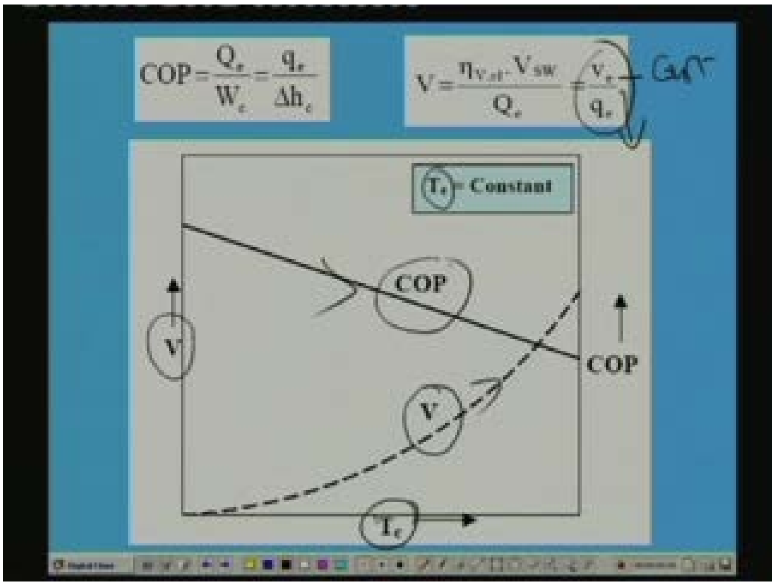

So as the result the COP reduces that is what is shown here the COP okay. It is reducing as condensing temperature is increasing. And again I have explained what is the effect of condensing temperature on the volume flow rate per unit capacity. That is nothing but the ratio of specific volume at compressor inlet and the refrigeration effect okay. So this remains constant at fixed Te. So the numerator does not vary but as you are increasing the condensing temperature the denominator is reducing. As a result the volume flow rate also increases that means the required size of the compressor increases if you keep the capacity constant.

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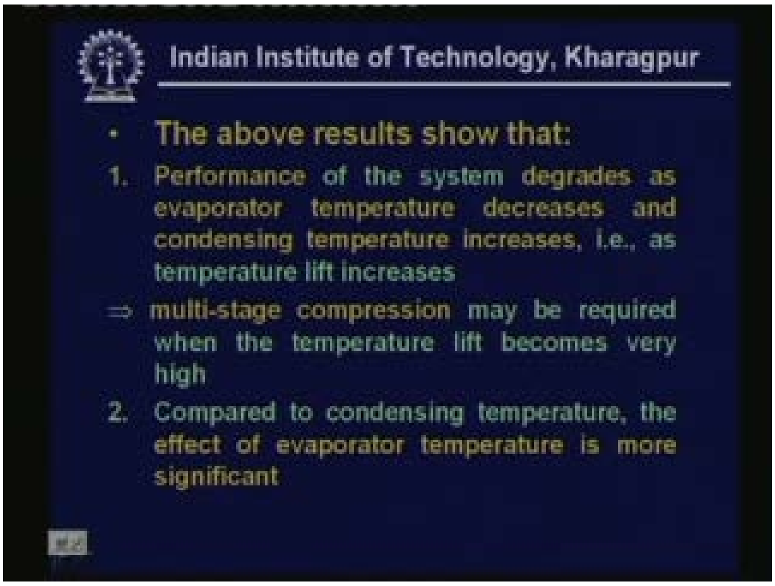

So from these above result that means from the effects of evaporator and condenser temperature on the system performance using this compressor we can conclude that performance of the system degrades as evaporator temperature decreases and condensing temperature increases. That means as temperature lift increases again this is in line with the effect of these temperatures on Carnot refrigeration system okay. This should be obvious because vapour compression system is developed from the Carnot refrigeration system only okay. This is a there are some deviations from Carnot cycle but it has to obey the basic principles okay. In Carnot cycle also as you increase the evaporator temperature COP increases as you reduce the condensing temperature COP increases okay. Same thing is observed here also and as we have seen here when the temperature lift becomes very high the performance may become very poor okay. In such cases we may have to go for multi-stage compression as we have discussed in our earlier lectures. And it is also seen that compared to condensing temperature the effect of evaporator temperature is more significant.

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Now let us look at the, another important performance parameter that is the discharge temperature okay. What is the problem if the discharge temperature is high if the compressor discharge temperature is very high then the lubricating oil may break-down resulting in excessive wear and reduced life of valves mainly the discharge valves. And ultimately the life of compressor also reduces when the discharge temperature is very high and because of high discharge temperatures undesired chemical reactions may take place especially in the presence of moisture. So why should there be moisture in the refrigeration system when you charge any refrigeration system initially there will be air inside the system okay, complete system will be filled with air. So normally you have to evacuate the system thoroughly. So that there is no air left inside the system and then charge the system with refrigerant. But it is not possible to perfectly evacuate any refrigeration system okay. So there will be some pressure inside. That means there will be some air and if that air consists of some moisture there will be some moisture within the system. In addition to that if there is any leakage then outside air may enter into the system.

So there is a possibility that moisture is present inside the refrigeration system okay, any refrigerant system. So when there is any moisture present inside the refrigeration system then there will be undecided chemical reaction between the refrigerant lubricating oil and moisture when the discharge temperature is very high okay. So this will ultimately affect the life of the compressor okay. So this is one bad effect of high discharge temperature. And in hermetic compressors the insulation on motor winding may burn leading to short-circuiting. And compressor damage we have seen in the last class that in hermetic compressors the motor has to be cooled using the suction gas itself okay. Because the motor and compressor both are kept in the same shell okay.

So if the discharge temperature is very high the whole of the compressor becomes hot okay. As a result the motor winding temperature also goes up okay. If the motor winding temperature becomes very high then the insulation on the winding may burn. Once the insulation burns the wires gets short-circuited once short-circuiting takes place the motor burns okay. So this is a typical problem in hermetic compressors. So because of these problems normally we should not operate any compressor beyond a certain discharge temperature okay. That means you have to operate it at as low as discharge temperature as possible okay. Now let us see how the discharge temperature is decided or what affects the discharge temperature.

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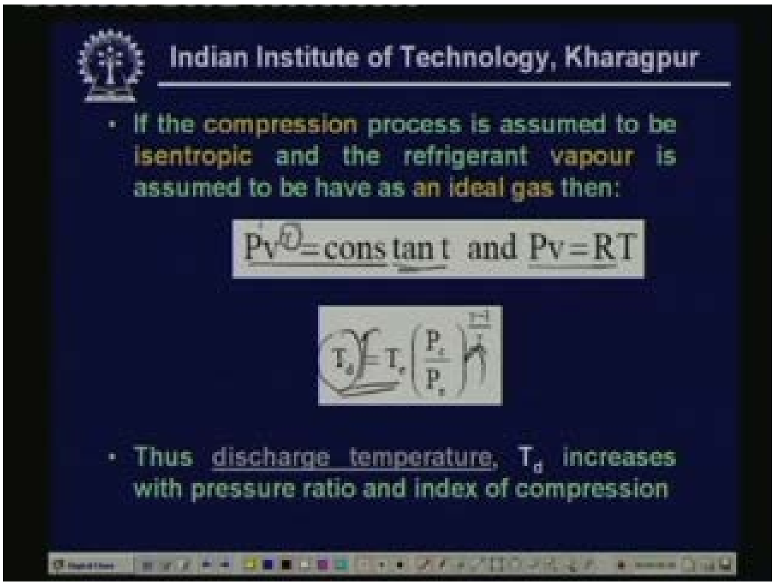

So if you assume the compression process to be isentropic and if you also assume that the refrigerant vapour to behave as an ideal gas. Then we can write these equations if the compression process is isentropic. Then we can write this equation where P is the pressure and v is the specific volume and gamma as you know is the ratio of specific heats okay. And for an isentropic process Pv to the power of gamma is constant and if the refrigerant vapour behaves as an ideal gas. Then we can write for the vapour Pv is equal to RT where R is the gas constant and T is the absolute temperature. So from these two equations we can derive this equation for the discharge temperature of the compressor okay. That means the discharge temperature at the exit of the compressor Td is equal to Te into Pc by Pe to the power of gamma minus one by gamma okay.

This is using these two equations okay. So from this equation you can very easily say that as Pc by Pe increases discharge temperature increases okay. Similarly as gamma increases discharge temperature increases. Let me show this on a figure.

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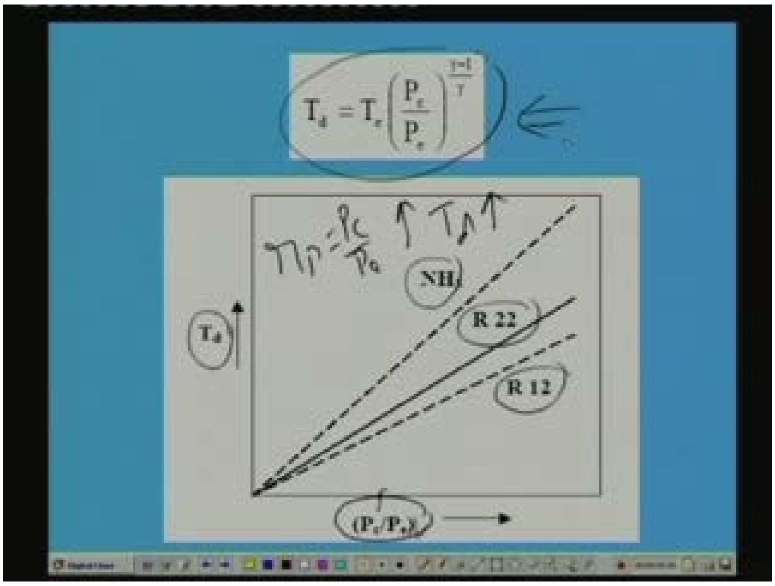

Okay, so this is the expression for discharge temperature and here we are varying the pressure ratio you are varying the pressure ratio means either you can increase the condenser pressure or you can reduce the evaporator pressure okay. So both will result in higher pressure ratio and discharge temperature is shown on the y-axis and the discharge temperature is, are shown for three different refrigerants ammonia R twenty-two and R twelve okay. First thing you notice here is that as the pressure ratio is increasing. That means as the pressure ratio Rp increases discharge temperature increases for a given refrigerant that is obvious from this equation okay.

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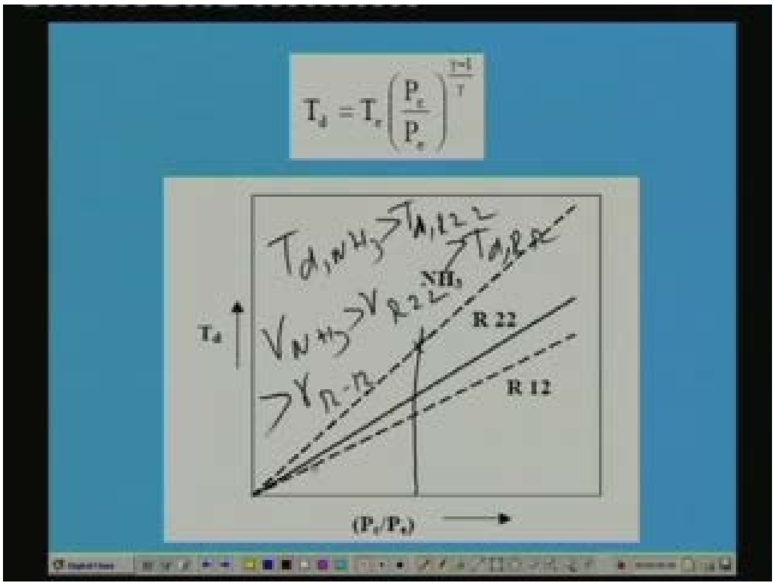

And at a given compression ratio discharge temperature of nitrogen I mean of ammonia sorry of ammonia is higher than discharge temperature with R twenty-two which is higher than the discharge temperature of R twelve okay. Why does it happen this happen because gamma of nitrogen I mean gamma of ammonia again sorry is greater than gamma of R twenty-two which is again greater than gamma of R twelve okay. That means since ammonia has high isentropic index of compression the discharge for the same pressure ratio the discharge temperatures of ammonia will be very high in fact okay. This is the reason why ammonia compressors require some external cooling okay.

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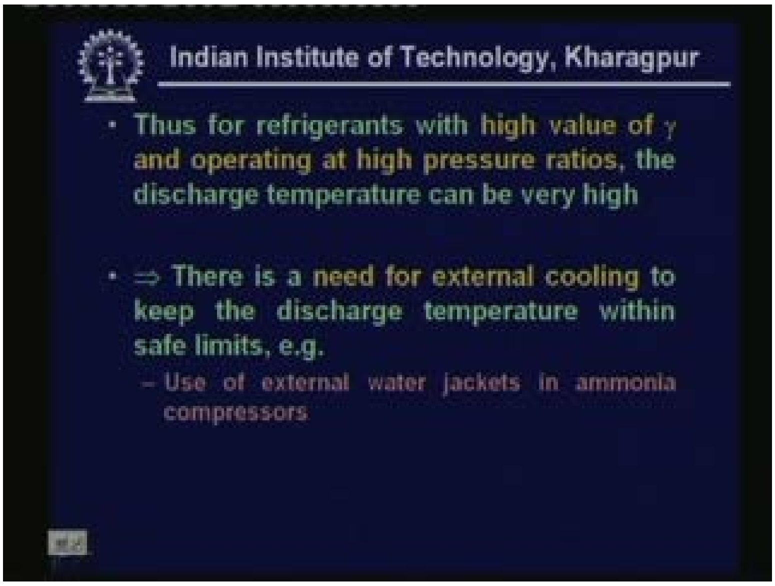

So thus for refrigerants with high values of specific heat ratio and operating at high pressures ratios the discharge temperature can be very high. This implies that there is a need for external cooling to keep the discharge temperature within safe limits. That means we can use for example external water jackets in case of ammonia compressors. So this is a very common practice if you look at any ammonia compressor there will be external water jacket welded to the outer body of the compressor. And water will be circulating through this water jackets and this water extracts the heat from the body of the compressor. So that the discharge temperature can be kept low.

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So for we have been discussing the performance of ideal reciprocation compressor first we discussed without clearance. And then we discussed the performance with clearance okay. Still the compressor is ideal okay, because we considered the processes to be reversible. We know very well that in actual case none of the processes are reversible okay. That means actual compressor deviates from ideal compressor okay. So if that is the case how does an actual compressor behave what is the effect of this operating temperature is on the performance of an actual compressor okay.

First let us look at the difference between an actual compressor and an ideal compressor okay. Actual compression process deviate from ideal compression processes due to three effects the first effect is heat transfer between refrigerant and surroundings during suction compression and expansion strokes okay. In the ideal compressor we neglected heat transfer we assume that all the process were adiabatic whereas in actual case they are non-adiabatic. And the second effect or second difference there will be frictional pressure drops in actual compressor which were neglected in case of ideal compressors. And what is the reason for this frictional pressure drops the frictional pressure drops in connecting lines across suction and discharge valves. All these are because of resistance to fluid flow okay and the third effect which we were neglected is leakage losses okay. So these are the three differences between an ideal compressor and an actual compressor. First let us look at the effect of heat transfer.

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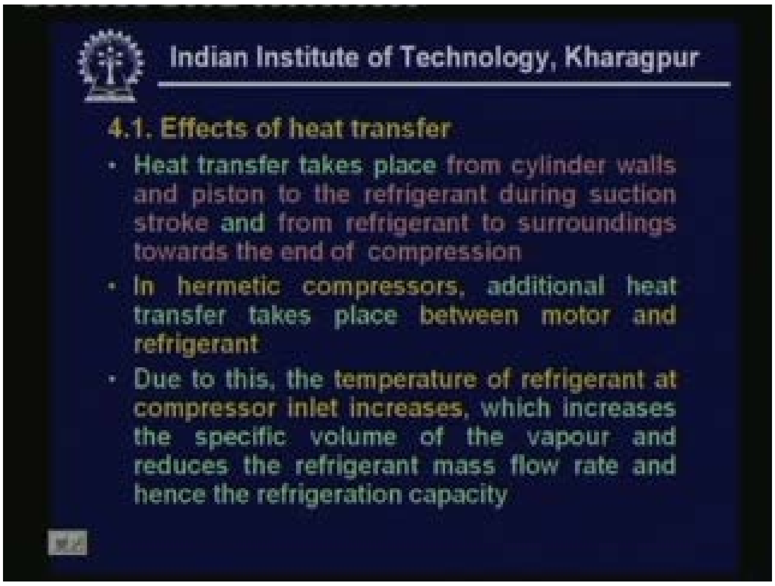

What happens because of the heat transfer heat transfer takes place from cylinder walls and piston to the refrigerant during suction stroke and from refrigerant to surroundings towards the end of compression. What does it mean when the refrigerant enters into the compressor the refrigerant is coming from the evaporator. That means it enters into the compressor at low pressure and low temperature okay. And during the initial phase of the suction process the refrigerant temperature will be lower than the surrounding temperature surrounding temperature means surrounding body temperature okay. So body will be hotter than the refrigerant that means there will be heat transfer from the surroundings to the refrigerant surroundings means the piston and cylinder walls etcetera.

Okay, that means the refrigerant vapour gets heated up during the suction process and at the end of compression we find that the refrigerant vapour temperature increases rapidly okay. So at the end of compression you find that the refrigerant temperature is higher than the surrounding temperature. That means the refrigerant rejects heat to the surroundings. That means during the beginning of suction the heat transfer is from the surroundings to the refrigerant and at the end of compression heat transfer will be from the refrigerant to the surroundings okay.

And in hermetic compressors as we know additional heat transfer takes place between motor and refrigerant due to this heat transfers especially during suction process the temperature of refrigerant at compressor inlet increases okay. So what is the problem if the refrigerant at the compressor inlet becomes hotter the problem is that it increases a specific volume of the vapour and reduces the refrigerant mass flow rate. Once the refrigerant mass flow rate is reduced the refrigerant capacity reduces okay. That means higher the inlet temperature smaller will be the density okay. That means for the same compressor displacement rate less mass of refrigerant will be pumped okay. The mass flow rate becomes less once the mass flow rate reduces as we know that refrigerant capacity of the system reduces okay. So this is a very important parameter.

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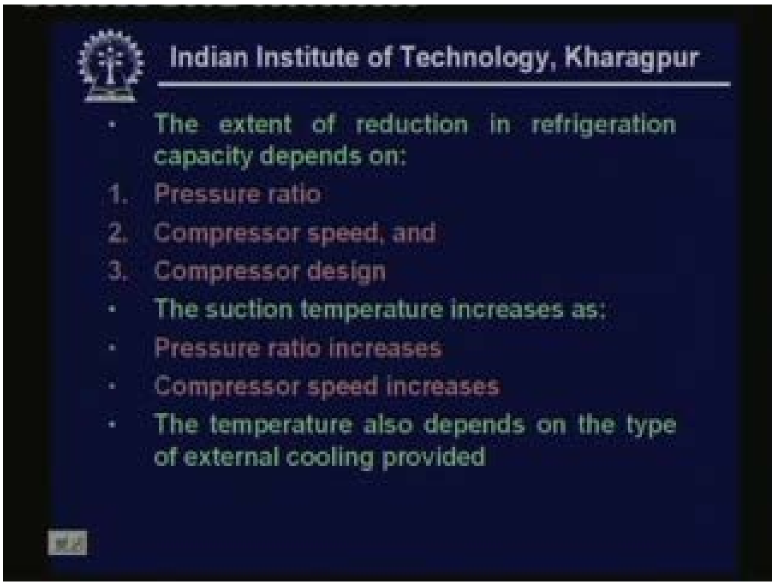

And what is the extent of reduction the extent of reduction in refrigeration capacity due to the heating depends on pressure ratio compressor speed and compressor. Design and the suction temperature increases as pressure ratio increases why does the suction temperature increases as the pressure ratio increases. We know that as the pressure ratio increases the discharge temperature increases. Once the discharge temperature increases the whole compressor body temperature increases. Once the compressor body becomes warmer then obviously there will be higher heat transfer from the compressor body to the cold suction gas as the result the suction temperature at the beginning of the compression increases okay. Then the suction temperature also increases as compressor speed increases. Why the suction temperature should increase when compressor speed increases. When the compressor speed increases more heat is generated within less time and less time is available for heat rejection. As a result energy gets trapped and the body becomes hotter once the body of the compressor becomes hotter there will be higher heat transfer from the body to the refrigerant vapour and the as the result its temperature increases okay.

And of course temperature also depends upon the types of external cooling provided. That means how the compressor body is cooled as we have seen if the discharge temperature is likely to become very high you have to provide external cooling okay, by way of water jackets or by way of external force convection using a fan or something like that okay. So what kind of external cooling that you are providing decides what is the temperature of the body of the compressor. And this in turn depends decides the suction temperature okay. In refrigerant such as R twelve where the discharge temperature is low normally no external cooling is provided by means of force circulation of air or water jackets okay. Natural circulation is enough but as the refrigerant changes from R twelve. Let us say ammonia the discharge temperature becomes very high okay. So we need external cooling. So once you provide external cooling the temperature of the body reduces once the temperature of the body reduces the suction temperature also reduces. So finally the suction temperature depends upon these three parameters that means the compressor speed pressure ratio and the type of cooling provided okay.

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And due to heat transfer compression and re-expansion processes are not adiabatic and depending upon the type of compressor. And external cooling the compression process may approach adiabatic process in case of centrifugal compressors centrifugal compressors. As we know run at very high speed okay. And they are quite compact for large capacities. So since they are compact and they run at very high speeds very less time is available for heat transfer to take place from the compressor to the surroundings or from the refrigerant to the surroundings okay. That means the centrifugal compressors compression process in centrifugal compressor almost approaches adiabatic compression process. Because of very less heat transfer okay.

And if it is a reciprocating compressor with cylinder cooling then the compressor process may approach reversible polytrophic process. We know that the polytrophic process is a general term, it is process with heat transfer okay. And when you have a reciprocating compressor normally the speed at which reciprocating compressors operate is less than the speed of centrifugal compressors okay. On top of it if you provide external cooling then there is a possibility of sufficient heat transfer from the cylinder from the compressor to the surroundings okay. That means the process will approach a polytrophic process okay. That means for reciprocating compressors one can use an assumption of reversible polytrophic process and for centrifugal compressors one has to use an, one can use an adiabatic process okay, for calculations.

And the index of compression in actual compressors depends on the process and is not a property of refrigerant if the compression process is reversible and adiabatic. That means if the compression process is isentropic we know that the index of compression k or gamma if it is behaving as an ideal gas is the property of the refrigerant okay. So it is decided by the type of the refrigerant okay. For a given operating conditions but if the process is polytrophic then the index of compression that is the polytrophic index of compression is no longer a property of the refrigerant it becomes a property of the process. That means how you are cooling it, as I said if you have a compression process with good amount of cooling then the index of compression could be lower than the isentropic index of compression. That means the index of compression of a reversible polytrophic process will be lower than the index of compression of an adiabatic process. On the other hand if the process is highly irreversible and the process is adiabatic. Then the index of compression will be higher than the reversible adiabatic index of compression okay. So ultimately the index of compression is what depends upon the type of process okay.

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Since the actual compression process is irreversible the actual work input will be greater than isentropic work okay. In all compressors and in all compression processes the actual compression will never be reversible adiabatic okay. It will always be irreversible due to heat transfer and due to pressure drops etcetera okay. So the actual work input will always be greater that the reversible adiabatic work input and we define an isentropic efficiency to estimate the actual work input. And this isentropic efficiency is defined as the ratio of isentropic work of compression divided by actual work of compression okay. In this expression this is isentropic work of compression and this is a actual work of compression for a given compressor isentropic efficiency is mainly a function of pressure ratio. So it is observed that from several tests on compressors that the isentropic efficiency for a given compressor depends mainly on the pressure ratio okay.

Once the pressure ratio is fixed it is observed that the isentropic efficiency is more or less fixed okay. And normally empirical equations are developed from measured test data to estimate isentropic efficiency okay. So normally the manufactures of the compressors they supply this information they give the expressions for isentropic efficiency as the function of pressure ratio okay. So depending upon your pressure ratio you can calculate what is the isentropic of efficiency of the, that particular compressor. So what is the use of this because you have to use this isentropic efficiency to estimate the actual power input to the compressor because you cannot calculate actual power input theoretically.

Theoretically what you can do is you can calculate what is isentropic work of compression if you know the operating temperatures and operating conditions okay. So the procedure for calculating the actual power input is like this first from the operating temperatures calculate what is the isentropic work of compression. Then from the expression for isentropic efficiency find out isentropic efficiency and then the actual power input is equal to isentropic power input divided by the isentropic efficiency okay. This is what is done normally to estimate the actual power input to the compressor.

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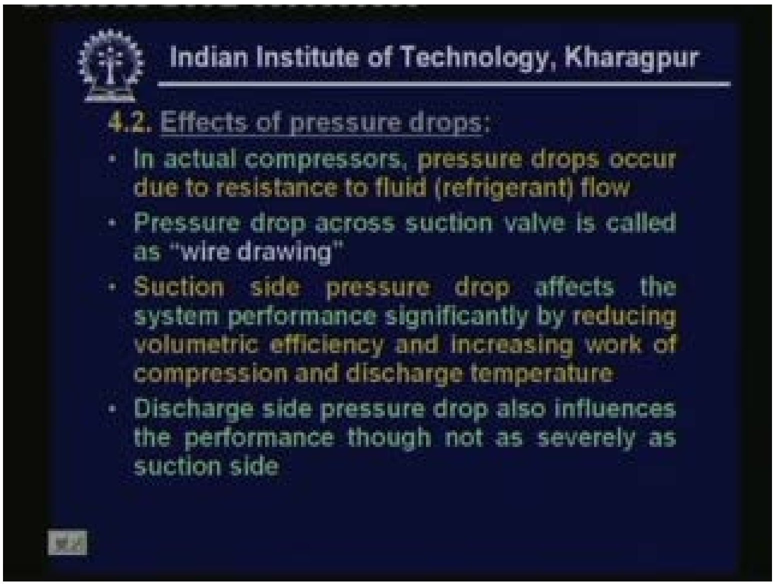

Now let us look at the effect of pressure drops. As I have already mentioned in actual compressors pressure drops occur due to resistance to fluid flow here fluid means refrigerant okay. So whenever refrigerant is flowing through connecting pipe lines or across the valves and all there will be some resistance. Because of this resistance there will be pressure drop and pressure drop across suction valve is called as wire drawing okay. This is a very important parameter why is it important suction side pressure drop affects the system performance significantly. Because as this pressure drop increases the volumetric efficiency is reduced and it also increases the work of compression and discharge temperature. So in practical cases the suction side pressure drop is very important and discharge side pressure drop is a also important. But it is not as important as suction side pressure drop. Let me show the PV diagram with pressure drops.

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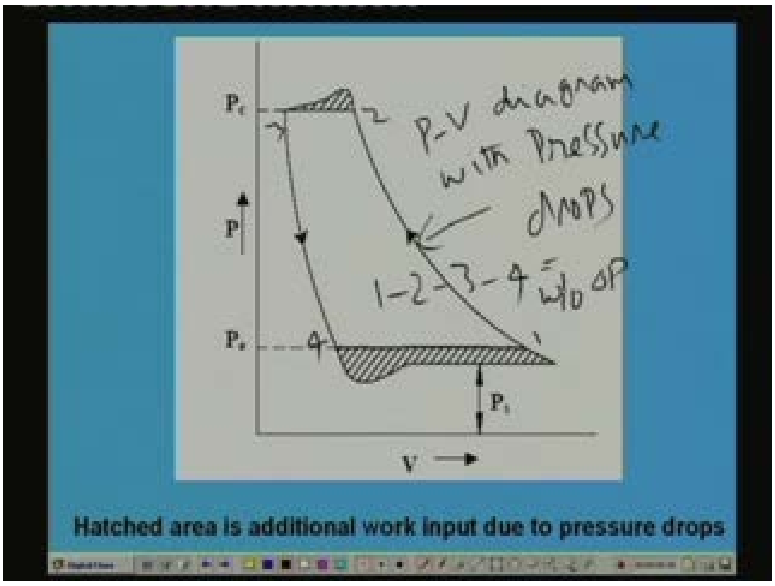

So this is the PV diagram with pressure drops. So you can see that had there be no pressure drop this would have been the compression process okay. Let us say that this, I am writing point one two three four. So one two three four is the PV diagram without any pressure drop okay, without delta P but with pressure drop the cycle becomes one dash.

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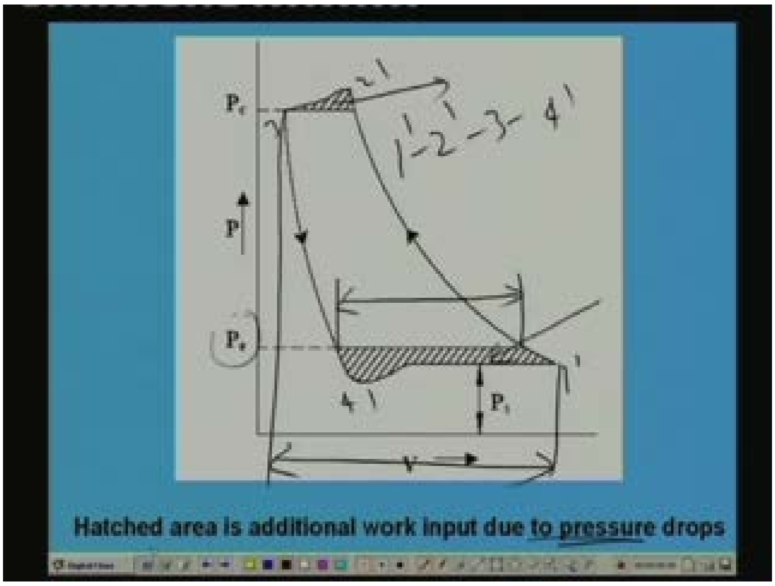

Let us say two dash three four dash okay the cycle becomes one dash two dash three four dash okay. So what is the effect of pressure drop on the volumetric efficiency you can see that the effect of pressure drop on volumetric efficiency is to reduce the volume of refrigerant compressed. What is the volume of refrigerant compressed at this evaporator pressure because of pressure drop it is equal to this okay. And what is the actual volumetric displacement rate what actual volumetric displacement rate is this okay. So you can see that because of the pressure drop this has reduced okay. And because of the pressure drop the area of the PV diagram has also increased and that increase is equal to this hatched area okay. This hatched areas are because of the pressure drops. So as a result of pressure drop on the suction side and on the discharge side you can see that.

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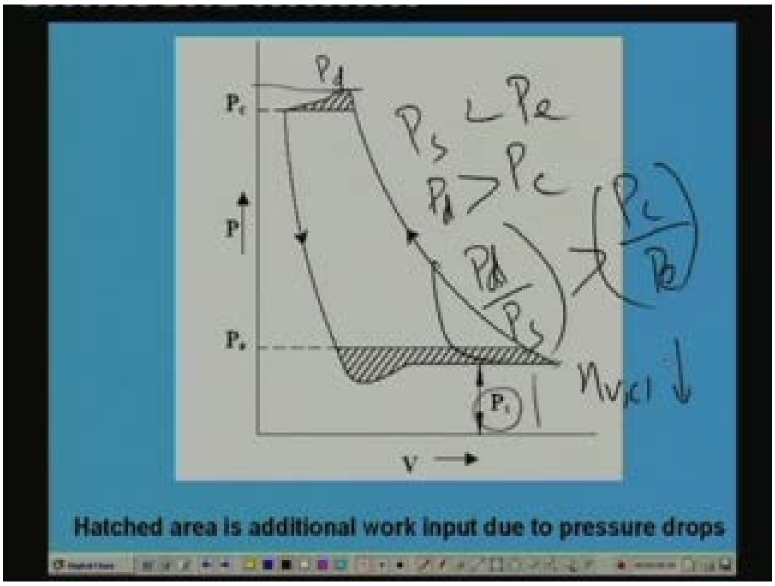

Work of compression also has increased okay. And that increase is equal to the hatched area and ultimately this is the pressure at which the compression is taking place okay. So at the inlet to the compression process the pressure is Ps and Ps is less than Pe okay. And similarly this is the discharge pressure. And discharge pressure Pd is greater than Pc that means that means Pd divided by Ps is greater than Pc divided by Pe okay. So as a result your volumetric efficiency reduces. Once the volumetric efficiency reduces mass flow rate reduces refrigeration capacity reduces in addition to that the work input is increasing. So ultimately the COP of the system gets affected.

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Now let us look at the effect of leakage losses in actual compressors refrigerant leakage losses occur across cylinder walls and piston across suction and discharge valves across oil seal in open type compressors. We did not consider this leakage while discussing ideal compressors but in actual compressor there will be leakage as and the magnitude of these losses depends on pressure ratio design of compressor valves. And life and condition of the compressor if the compressor is old the leakage losses will be high okay. And if the pressure ratio is high the leakage losses will be more and if the valves are not designed properly then again there will be higher leakage losses.

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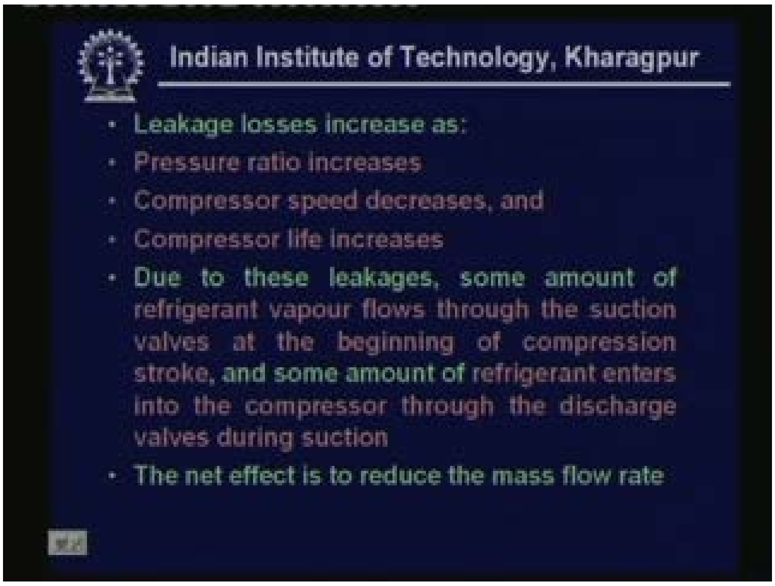

And leakage losses increase as I have already mentioned with pressure ratio and leakage losses increase as the compressor speed is decreased and the leakage losses also increase with compressor life. So due to these leakages some amount of refrigerant vapour flows through the suction valves at the beginning of compression stroke. And some of the amount of refrigerant enters into the compression compressor through the discharge valves during the suction okay. So some that means some refrigerant escapes out of the suction valve at the beginning of the compression stroke. Similarly at the beginning of the suction stroke some refrigerant from the condenser enters into the compressor that there will be some flow as a result of this the net mass flow rate reduces. Once the net mass flow rate reduces the refrigerant capacity reduces.

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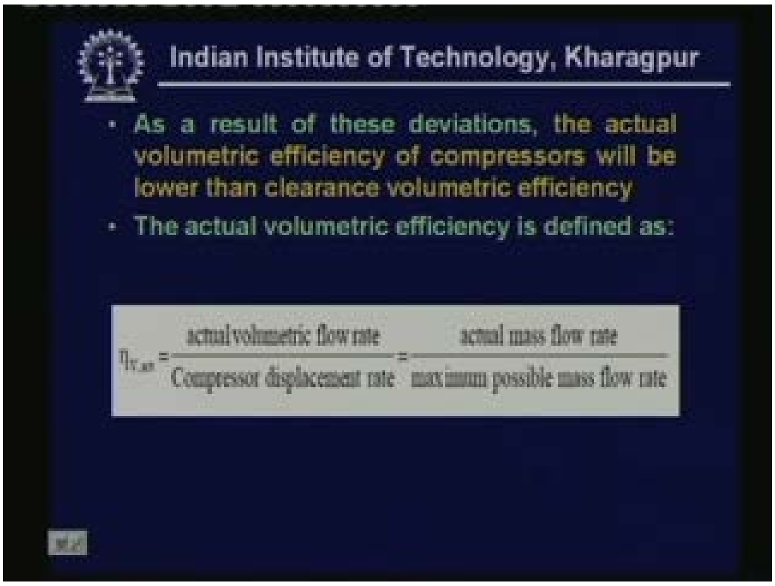

So as a result of all these deviations the actual volumetric efficiency of the compressors will be lower than clearance volumetric efficiency and the actual volumetric efficiency can be defined in terms of volumetric flow rates or also in terms of mass flow rates as shown here. So it is the ratio of actual volumetric flow rate divided by the compressor displacement rate or actual mass flow rate divided by the maximum possible mass flow rate.

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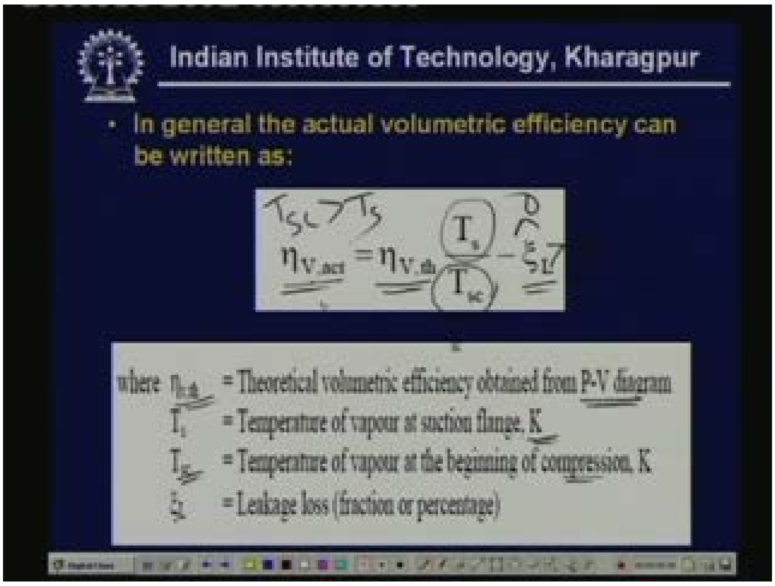

And in general the actual volumetric efficiency can be written as there is a, there is an expression for actual volumetric efficiency. It is written in terms of theoretical volumetric efficiency temperature of vapour at suction flange and temperature of vapour at the beginning of compression and leakage losses. So here as I said this is the theoretical volumetric efficiency obtained from P-V diagram Ts is the temperature of vapour at suction flange and Tsc is the temperature of vapour at the beginning of compression okay. Because of cylinder heating and all that Tsc will be greater than Ts. Since Tsc is greater than Ts and this leakage losses will be greater than zero this will be greater than zero you will find that actual volumetric efficiency will be less than the theoretical volumetric efficiency.

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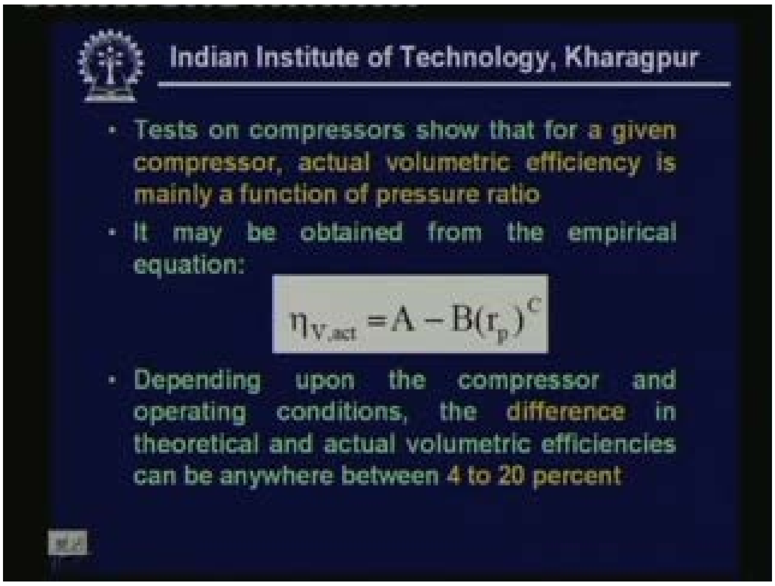

And tests on compressors show that for a given compressor actual volumetric efficiency is a mainly a function of pressure ratio. That means if you fix the compressor the actual volumetric efficiency depends mainly on the pressure ratio only. And from several tests on compressor it is generally shown that the actual volumetric efficiency can be written as A minus B into rp to the power of C where rp is the pressure ratio Pc by Pe. And A B C are some empirical constants which depend on the type of the compressor and the operating pressure range okay. And depending upon the compressor and operating conditions the difference in theoretical and actual volumetric efficiencies can be anywhere between four to twenty percent okay. So difference can be as large as twenty percent or it can be as small as four percent in a well designed compressor okay.

So normally just like isentropic efficiency of the compressor the manufacturers may supply the expressions for actual volumetric efficiency okay. So from the actual volumetric efficiency you can find out what is the actual mass flow rate and from that you can find out what is the refrigeration capacity okay. That is how you can estimate the performance of actual refrigeration systems okay. With this I will conclude this lecture.

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In this lecture we have discussed the following topics effect of evaporator. And condenser temperature in the performance of an ideal compressor with clearance variation of discharge temperature with operating conditions. And deviation between ideal and actual compressors and finally performance aspects of actual compressors okay. We will continue this in the next lecture. Thank you.