Refrigeration and Air Conditioning
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Lecture No. # 20
Refrigeration System Components
Compressor

Welcome back. As we have seen from our earlier lectures a refrigeration system consists of several basic components such as compressors, condensers, evaporators, expansion devices. In addition to it there will be several accessories such as controls safety devices etcetera. The performance of any refrigeration system depends upon the individual performance of these components. And how well there are balanced when assembled okay. So before we study the performance of the complete system. Let us look at the performance aspects of these individual components. So let us begin this discussion with compressor which is called as the heart of any vapour compression refrigeration system.

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So the specific objectives of this particular lecture are to classify refrigerant compressors, introduce open hermetic and semi-hermetic compressors, discuss important performance parameters, discuss performance of an ideal compressor without clearance and finally discuss performance of an ideal compressor with clearance.

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So at the end of this lecture you should be able to list different types of refrigerant compressors, explain open hermetic and semi-hermetic compressors and their characteristics list important performance parameters, evaluate the performance of an ideal compressor without clearance and finally evaluate the performance of an ideal compressor with clearance.

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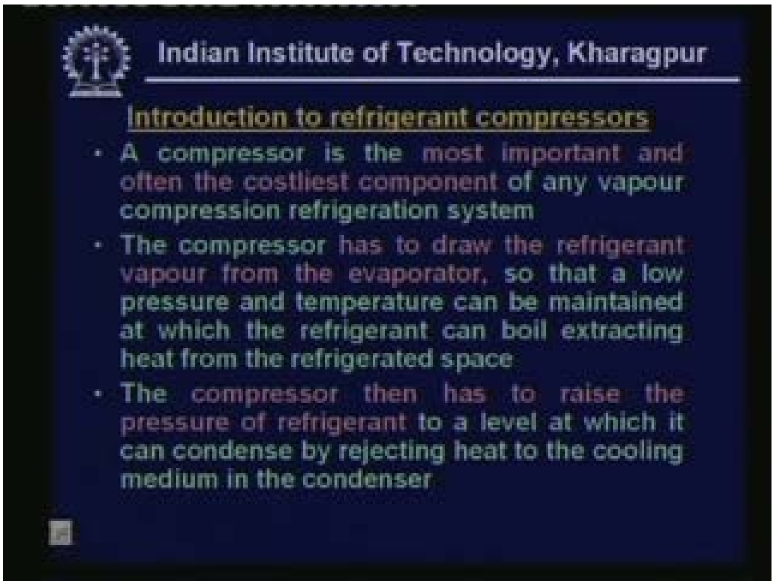

Let me give a brief introduction to compressors a compressor is the most important and often the costliest component of any vapour compression refrigeration system typically thirty to forty percent of total plant cost is because of the compressors. So it is a very important component the compressor. What is the function of the compressor? The compressor as you know has to draw the refrigerant vapour from the evaporator. So that a low pressure and temperature can be maintained at which the refrigerant can boil extracting heat from the refrigerated space.

So this is the first objective not only that it also has to raise the pressure or refrigerant to a level at which it can condense by rejecting heat to the cooling medium in the condenser. That means typically a compressor will have a suction side and a discharge side on the suction side refrigerant vapour from the evaporator enters into the compressor. This refrigerant vapour gets compressed in the compressor and its discharged to the condenser where it can condense. So this is the primary objective of any compressor.

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Compressors can be classified based on the working principle for example as positive displacement type of compressors Roto-dynamic type of compressors. We can also classify them based on the arrangement of compressor motor or external drive and based on this particular type. We can have open type compressors or we can have hermetic or sealed type compressors or semi-hermetic or semi-sealed type compressors.

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Now let us look at positive displacement type of compressors in these compressors compression is achieved by trapping a refrigerant vapour into an enclosed space and then reducing its volume. Since a fixed amount of refrigerant is trapped each time its pressure rises as its volume is reduced. When the refrigerant pressure inside the compressor rises to the level of condensing pressure then the refrigerant is expelled from the enclosed space and a fresh charge of refrigerant is drawn in and the cycle continues. That means initially we have to taking certain amount of refrigerant vapour in an enclosed space using piston cylinder valves etcetera. And then reduce the volume of this refrigerant. So that its pressure can raise and when this pressure rises to the level of condenser pressure. Then the refrigerant is expelled from the compressor and fresh charge is taken in. So this is the working principle of a positive displacement type of compressor.

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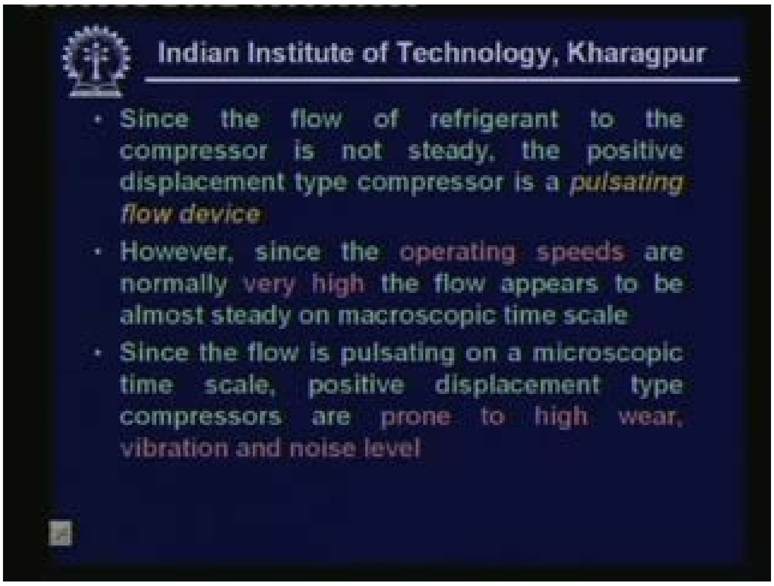

Since the flow of refrigerant to the compressor is not steady the positive displacement type compressor is a pulsating flow device. So you can see that during one stroke you have suction and during one stroke. You have compression and during the other another stroke you have discharge. So the flow rate of refrigerant is not steady so it's basically a pulsating flow device. So however since the operating speeds are normally very high. That means rotational speeds of the compressors are so high that the flow appears to he almost ready on macroscopic time scale. However since the flow is pulsating on a microscopic time scale positive displacement type compressors are prone to high wear vibration and noise level. So this is the one problem of with positive displacement type of compressors.

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The positive displacement type compressors can be classified into reciprocating type rotary type with sliding vanes again rotary type can be either rolling piston type or multiple vane type. We can also have rotary screw type either single screw or twin screw type orbital compressors and finally acoustic compressors.

(Refer Slide Time: 05:43)

So let us look at roto-dynamic compressors in these compressors. The pressure rise is achieved by imparting kinetic energy or angular momentum to a steadily flowing stream of refrigerant by a rotating mechanical element. And then converting the kinetic energy into pressure as the refrigerant flows through a diverging passage. That means what is done is charge of refrigerant is taken into the compressor steadily and angular momentum is imparted to this refrigerant by a high speed rotating mechanical element such as a blade of the compressor. As a result the kinetic energy of the refrigerant increases then this kinetic energy is converted into pressure by forcing the refrigerant to flow through a diverging passage. So this is the working principle of roto-dynamic compressors unlike positive displacement type compressor roto-dynamic type compressors are steady flow devices. Hence they are subjected to less wear and vibration. So this is an advantage of roto-dynamic compressors.

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Roto-dynamic type compressors can be classified into radial flow type or axial flow type centrifugal compressors or turbo compressors are radial flow type compressors. And these are widely used in large capacity refrigeration and air conditioning systems axial flow type compressors are not normally used in air conditioning. But there are used in certain special applications such as gas liquefaction.

(Refer Slide Time: 07:07)

Now, let us look at open type compressors what do you mean by open type compressor in open type compressors the rotation shaft of the compressors extends through a seal in the crankcase for an external drive. The compressor may be belt driven which is more common or gear driven. It is rarely gear driven but in principle you can have gear drive. The external drive may be an electric motor or an external engine. For example one can use a steam engine or a diesel engine for running the compressor. Open type compressors are normally used in medium to large capacity refrigeration systems for all refrigerants and also for ammonia for all capacities. So let me explain an open type compressor.

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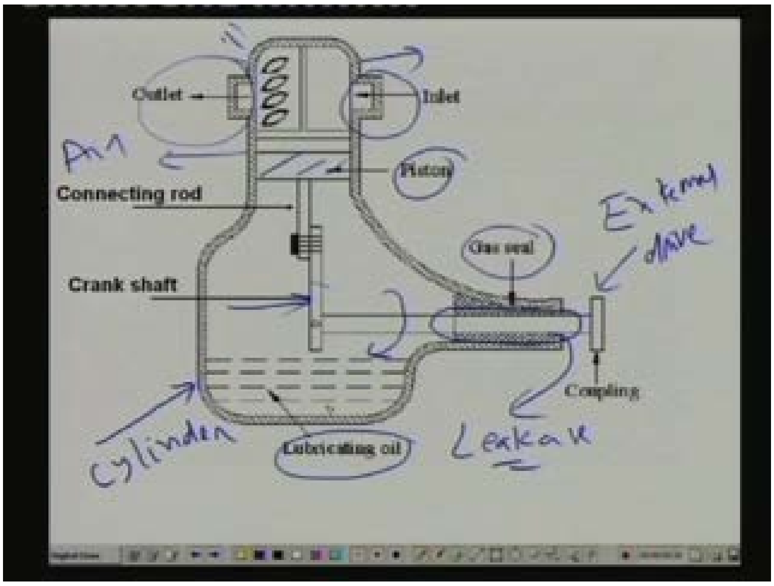

So you can see that the, this figure here shows the open type compressor. This is the cylinder and you have the piston here. This is the piston and you have the inlet section here and then outlet okay. And you can see that we also have a connecting rod which connects the piston with the crank shaft here, the, this is the crank shaft okay. So the connecting rod connects the piston and the crank shaft. And this in turn comes out of the body of the cylinder through a gas seal here and is connected to an external drive. So here it is connected to an external drive. So you can use either belt drive or gear drive and you can connect it, this drive to this. It can be coupled to a electric motor or an engine okay.

So one of the problems with this type of compressors as you can see is this shaft has to rotate. So certain clearance must be provided at the seal. So that it can rotate without too much of friction. So when you are providing certain amount of gap here there is a possibility of refrigerant leakage okay. So this is one typical problem with the open type of compressors. However as usual we see later these compressors have higher efficiency and the heat of compression can be rejected directly to external air okay. So heat rejection can take place externally. Normally these compressors are connected to service valves at the inlet side and the outlet side and at the bottom of the cylinder you have a oil sump where lubricating oil is stored.

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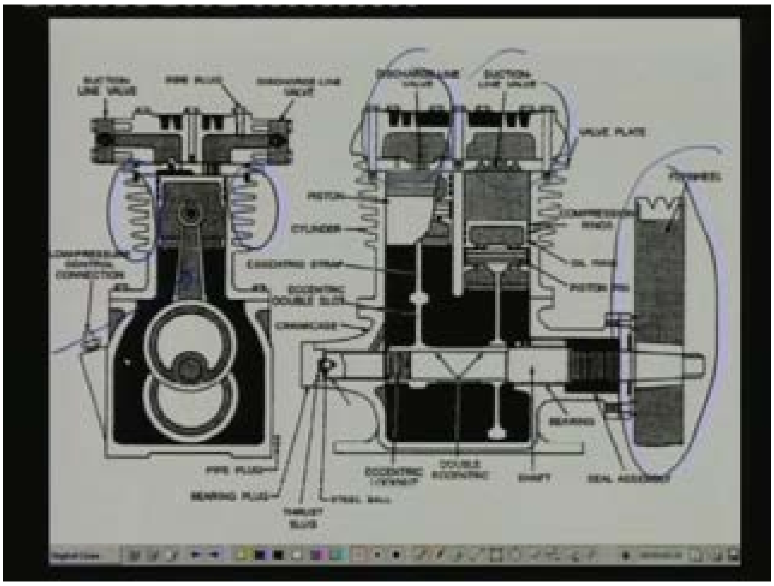

This in fact shows the sectional view of a, an industrial two cylinder open type compressor is a vertical arrangement. So you can see the fins here for okay. So let me go back you can see the fins here for heat rejection and you can see several components. This, since is the actual compressor there are many other components. And basically you can see the discharge valve there are two compressors here. So you have the manifolds for discharge and suction lines here. And you have the fly wheel which is connected to a elt drive or a gear drive and this is the connecting rod and the crank shaft etcetera.

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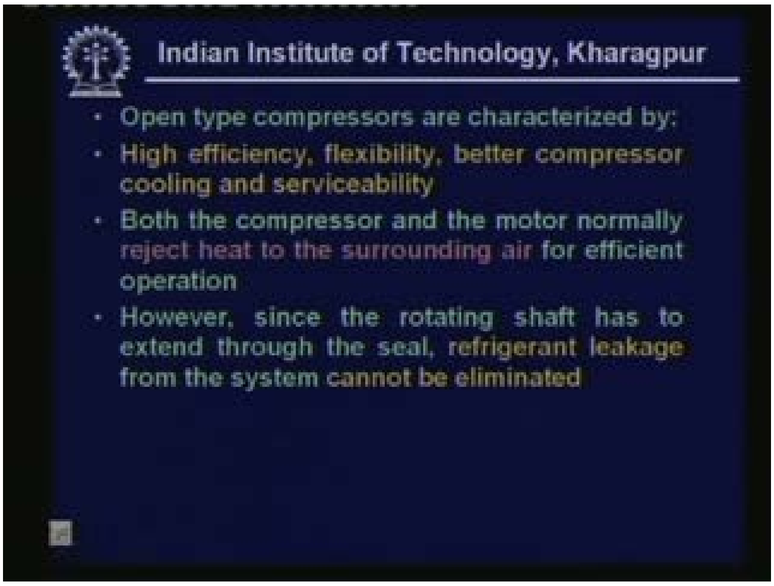

So what are the characteristics of open type compressors open type compressors are characterized by a high efficiency flexibility better compressor cooling and service ability. Why do we get high efficiency we get high efficiency because both the compressor and the motor normally reject heat to the surrounding air. As a result the heat rejection from the compressor and motor do not become a part of the refrigeration load hence you get higher efficiency. And these systems are flexible because you can vary the speed of the compressors. Because if you have a belt drive you can vary the speed and if you have a gear drive also you can vary the speed. So they offer flexibility another advantage of these compressors is if you are using a belt drive there is no possibility of motor getting overloaded. Because if the compressor is overloaded. Then the belt starts slipping okay. So this is the another advantage of open type compressors.

Normally open type compressors are used in large systems because they are serviceable okay they are not use and throw type. So you can service them. You can replace a valves. You can replace the gaskets etcetera oaky. So that is the reason why they find applications in large systems. However they have one problem. As I have already explained the rotating shaft has to pass through a seal. So there is a continuous refrigerant leakage through the seal. Of course the leakage can be minimized by designing the seal properly but it cannot be eliminated completely. So you have a continuous refrigerant leakage from the system okay. So to take care of these refrigerant leakages you have to have a refrigerant reservoir inside the system which will take care of the refrigerant leakage to some extent.

However after certain time you have to charge the system with refrigerant okay. That is the reason they require a periodic servicing. Since the periodic servicing is possible in large system where people are available for to do the servicing there normally used in large capacity systems. In addition as I have already told you since they offer higher efficiency and higher efficiency is very important in large capacity systems. In all large capacity system the open type compressors are used okay.

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So as I have already explained these system these compressors require refrigerant reservoir and regular maintenance.

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Now let us look at hermetic compressors. These are also known as seal type of compressors. In these compressors the motor and compressor are enclosed in the same housing. So this prevents refrigerant leakage. The housing has welded connections for refrigerant inlet and outlet and for power input socket. As a result of this there is virtually no possibility of refrigerant leakage from the compressor. So the hermetic compressors has been developed to take care of the problems posed by open type of compressors typically refrigerant leakage which calls for periodic maintenance. Periodic maintenance as I have already told you is possible in large systems where service personnel are available. But you cannot have a regular maintenance in for example say domestic refrigerators room air conditioners. So as a result of which people have developed the hermetic compressors which are leak proof okay. So how do we get a leak proof arrangement let me show the figure okay.

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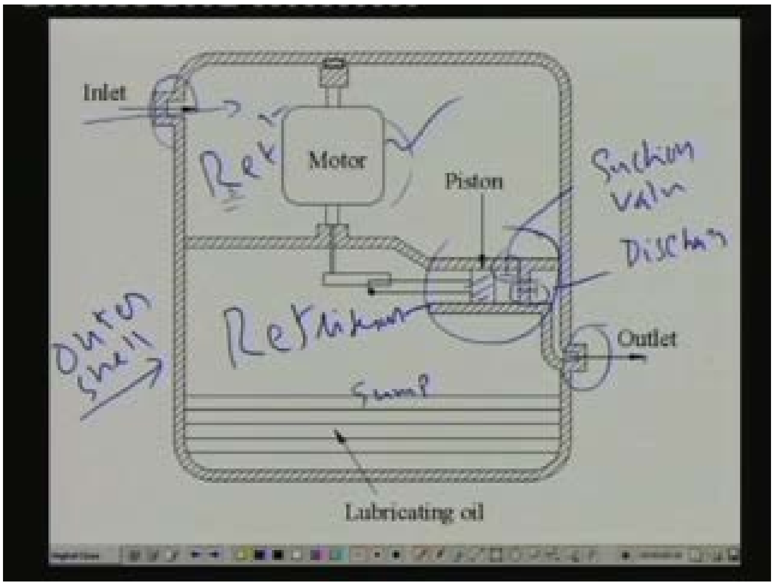

So here this shows the schematic of her hermetic compressor you have an outer casting this is an outer or outer shell. So both the motor and the compressor are housed in the same housing okay. So there is no possibility of refrigerant leakage. For example from this point if there is any refrigerant leakage from the compressor if the refrigerant stays inside the outer shell okay. So you have the refrigerant contained within in the shell okay. And the connections are typically welded. So you have permanent connection at the inlet and the outlet. So there is no possibility of refrigerant leakage. So in this particular arrangement the refrigerant enters like this and it cools the motor. And it also cools the compressor and then it enters through this suction valve you have the suction valve here.

Okay, into the compressor this is the piston of the compressor and its gets compressed and when the pressure raises above the condensing pressure this discharge value. This is the discharge valve discharge valve opens and refrigerant goes out of the outlet to the condenser. So the and again you have a lubricating oil sump here okay. So as you can see that the advantage of this compressor are virtually there is no refrigerant leakage. And since both motor and compressor are kept in the same housing the noise levels are also typically lower in this case compared to an open type of compressor. So you can see that the compressor is directly mounted on the motor shaft. So the, this poses a problem for example when the compressor is overloaded motor also gets overloaded. Okay. And since refrigerant comes in contact with the motor winding there must be compatibility with them between the insulation on the motor winding and the refrigerant. So that is very important here.

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So this shows the cut view of an industrial refrigerant compressor of hermetic type. So you can see the copper winding here okay. And this is the outer shell and these are the connections for inlet and outlet and this is for the electrical connections. So from the outside you really do not seen anything you just see a shell and two two connections one for the suction line and the other for the discharge line and the electrical connections okay. So this is the typical hermetic compressor is used in small capacity systems.

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So in hermetic compressors as we have seen heat cannot be rejected completely to the surrounding air since both motor and compressors are enclosed in a shell as explained. Hence the cold suction as is made to flow over the motor and the compressor before entering into the compressor. That means the suction gas itself is used to keep the motor and compressor cool. As a result of which motor remains cool however it reduces the efficiency of the refrigeration system. How does it reduce the efficiency? Because the heat rejected by the motor and compressor are picked by the refrigerant itself. So finally it hast o be reject. It has to be taken out at the evaporator. That means the inefficiencies of the motor and compressor become a part the refrigerant load which consumes higher power okay. Because you have to provide extra refrigeration effect to take care of these heat rejections. As a result all hermetic type of compressors offer typically lower efficiencies compared to open type of compressors okay.

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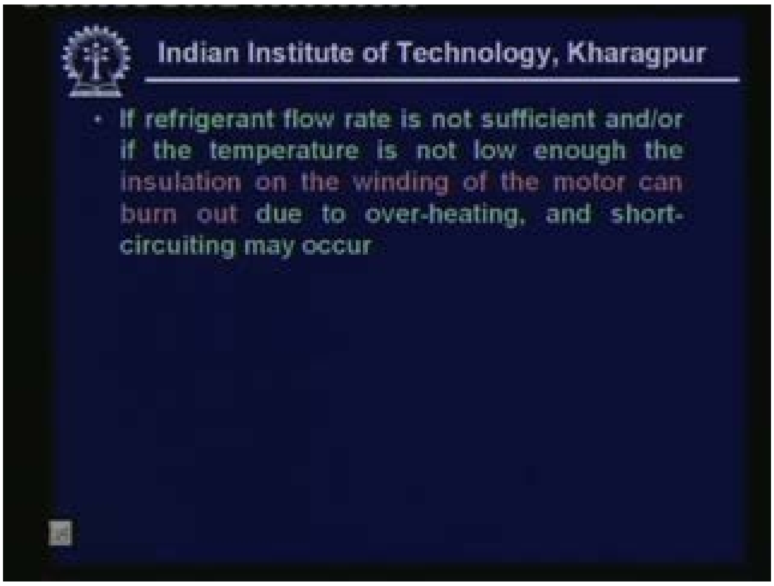

And another problem is if the refrigerant flow rate is not sufficient and or if the temperature is not low enough the insulation on the winding of the motor can burn out due to over-heating and this may result in short circuiting. This is actually a serious problem for example you have designed the motor and compressor for certain operating condition. And the operating conditions change as a result the refrigerant flow rate reduces and also its temperature increases.

So when its flow rate reduces and its temperature increases the capacity of the refrigerant to take out the heat from the motor and compressor reduces. As a result the motor temperature increases the winding temperature increases. When the winding temperature increases beyond a certain point the insulation on the winding may burn out okay. So once it burns out short circuiting of the winding takes place and the motor gets damaged okay. So this is a major problem in hermetic compressors. So normally hermetic compressors are not used for over a wide range of operating conditions the work satisfactorily over a very narrow range of operating condition sum okay.

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So as I said they perform only over a narrow range of operating conditions. And as I have already explained the motor winding is in direct contact with refrigerant. Hence only those refrigerants which have high dielectric strength can be used in domestic refrigerants okay. I mean in hermetic compressors you cannot use all kinds of refrigerant. You have to have good compatibility between the winding and the refrigerant.

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So hermetic compressors are widely used in applications where efficiency is not as important as customer convenience. That means in domestic refrigerators and room air conditioners. How does it ensure customer convenience? Because this is free from refrigerant leakage. So the customer need not call the service personnel everyday to charge the system okay. So once you charge the system with refrigerant it can run for years together without any servicing. This is what is required in small systems where regular maintenance is not possible okay. And this is the factor which has, which is more important than efficiency in small systems. Because in small systems small increase in efficiency is not as important as the customer convenience okay. So this is the reason why we use hermetic compressors in small capacity systems such as domestic refrigerators small room air conditioners water coolers etcetera, okay. And these systems we shall see later.

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Or also ideal in systems which use capillary tubes as expansion devices. And as I have already told you hermetic compressors also offer low noise levels okay. But one problem with these compressors are there are not very flexible because of the limited operating range. And you cannot also vary the speed to much because once you vary the speed it may affect the compressor cooling okay.

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Now let us look at the third type of compressor. That is called as semi-hermetic or semi-sealed compressors this some trade off between open type and hermetic type of compressors.

In some larger capacity hermetic units the cylinder head is removable. So that the valves and the piston can be serviced. That means basically a semi-hermetic compressor is a hermetic compressor with a provision of limited servicing okay. Limited servicing means you can have access to the valves and you can have access to the piston. So this type of unit is called the semi-hermetic or semi-sealed compressor. So this compressor as I have already told you offers limited serviceability semi-hermetic compressors are commonly used in factory assembled units such as packaged air conditioners.

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Now let us look at positive type displacement a compressors that is first let us look at reciprocating compressor. As the name implies the reciprocating motion of piston in the cylinder gives rise to suction and compression in a reciprocating compressor. Let me explain the working principle.

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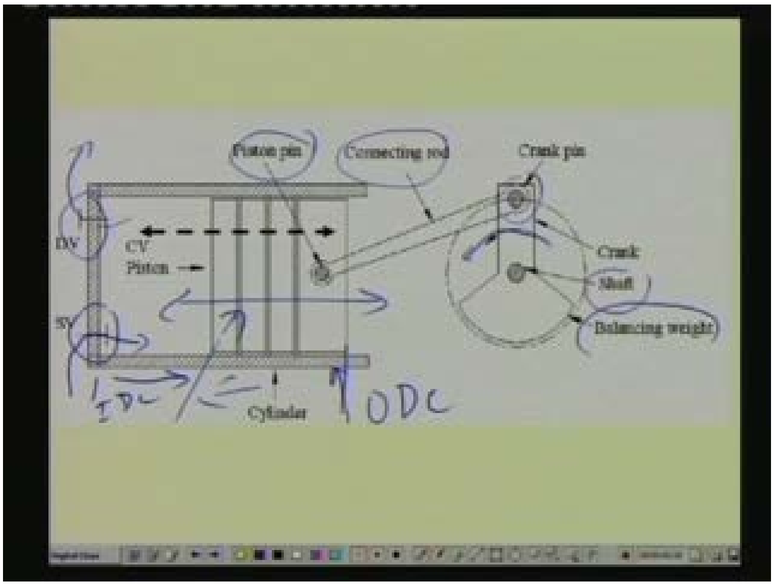

So you have, as you can see that you have a cylinder here, suction valve, discharge valve, this is the piston and the piston is connected to the crank shaft by a connecting rod. And the crank shaft is connected to the shaft and their balancing weight is provided for balancing of the system. And the connecting rod and piston are connected by a piston pin. And the connecting rod and crank shaft are connected by a crank pin. And the, connect crank shaft will be basically rotating in this direction. So the rotation of the crank shaft gives a motion of the piston. So as the piston moves in this direction suction and compression takes place. For example let us say that the piston is initially at this position okay, which you call it as inner dead centre okay. So and from this point as this moves in this direction the pressure inside the cylinder falls.

Once the pressure inside the cylinder falls the suction valve opens and refrigerant enters into the compressor. This process takes place as long as this is moving towards the, what is known as the outer dead centre. And during the reverse stroke the piston starts moving from the outer dead centre to the inner dead centre. So pressure builds up inside the cylinder as the pressure builds up the suction valve closes. But since the pressure is lower than the discharge side pressure discharge valve pressure also will remain close. That means during this process, during the compression process both the suction valve as well as discharge valve remain closed.

And the volume of the refrigerant trapped inside the cylinder is reduced because the movement of the cylinder. As the result the pressure raises. And once the pressure raises to the level of the discharge pressure the discharge valve opens and the refrigerant goes out of the discharge valve to the condenser due to the motion of the piston in this direction

Okay. So and again the during the reverse stroke this starts moving in the opposite direction again next cycle of compression starts okay. So these working principle of a reciprocating compressor.

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Reciprocating compressor is most important type of compressor because it is the workhorse of refrigeration and air conditioning industry. And these compressors are available in capacities ranging from a few watts to hundreds of kilowatts. And modern day reciprocating compressors are high speed. That means about three thousand to three thousand six hundred revolutions per minute. They are normally single acting and they are either single or multi-cylinder type multi-cylinder means a single compressor can have as many as sixteen cylinders.

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Now let us look at performance of reciprocating compressors for a given evaporator. And condenser pressures important performance parameters of any refrigerant compressor are, first one is the mass flow rate for a given compressor size or the volumetric capacity. That means what is the refrigeration capacity per metre cube of the compressor size this is the first important performance parameter. Second important parameter is what is the power consumption per unit refrigeration capacity expressed in kilowatt of power consumption per kilowatt of refrigeration capacity. This is the reverse of your inverse of your COP. Then the third important parameter is what is the discharge temperature of the refrigerant at compressor exit. And fourth important performance parameter is, how does the compressor perform under part load conditions. So these are the four important parameters of any refrigerant compressor.

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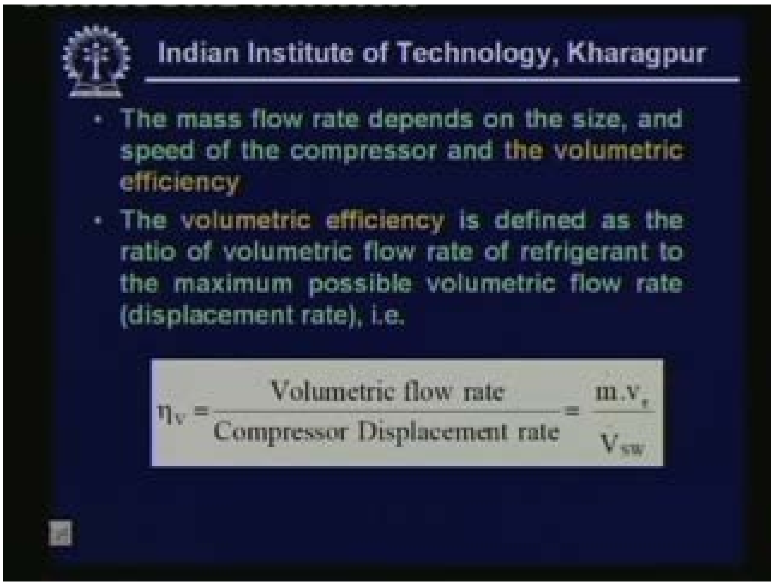

The mass flow rate of any compressor depends upon the size and speed of the compressor and also on the volumetric efficiency. So what is volumetric efficiency? The volumetric efficiency is defined as the ratio of volumetric flow rate of refrigerant to the maximum possible volumetric flow rate. The maximum possible volumetric flow rate is also called as displacement rate of the compressor. That means the volumetric efficiency is defined as you can see from the equation volumetric flow rate divided by the compressor displacement. The volumetric flow rate in metre cube per second can be expressed as a product of mass flow rate of refrigerant in kilogram per second into the specific volume of the refrigerant at compressor inlet Ve which is in kilogram per metre cube okay, divided by compressor displacement given by V dot SW.

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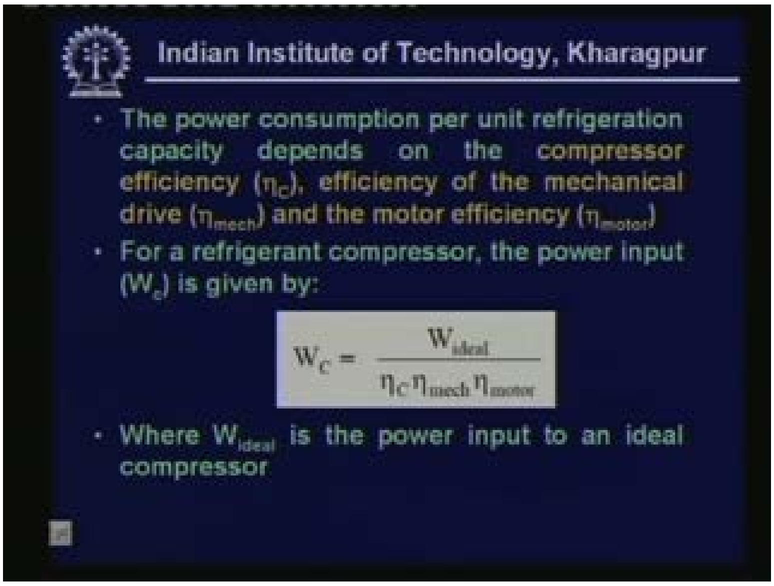

So next important parameter as I mentioned is the power consumption per unit refrigeration capacity. This depends upon the compressor efficiency eta C efficiency of the mechanical drive eta mechanical and the motor efficiency eta motor. So for a given refrigerant compressor the power input is given by Wc is equal to W ideal divided by eta C into eta mechanical into eta motor. As I said eta C is the compression efficiency eta mechanical is the mechanical efficiency and eta motor is the motor efficiency. And here W ideal is the power input to an ideal compressor we will see what is an ideal compressor little later.

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So the third important parameter I have already mentioned is the temperature at the exit of the compressor or the discharge temperature. The discharge temperature depends upon the type of refrigerant used and the type of compressor cooling for a given evaporating and condensing pressures okay. What is the importance of this parameter has a bearing on the life of the compressor so this is very important practical parameter. And the fourth important performance parameter is the performance of the compressor under part load conditions. This depends on the type and design of the compressor.

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Now let us look at an ideal reciprocating compressor. So how do you define an ideal reciprocating compressor an ideal reciprocating compressor is one in which the clearance volume is zero. I will explain what is the clearance volume and there are no pressure drops during suction and compression. And all the processes such as suction compression and discharge are reversible and adiabatic. So this all this three criteria must be satisfied for a compressor to be called as an ideal compressor without clearance.

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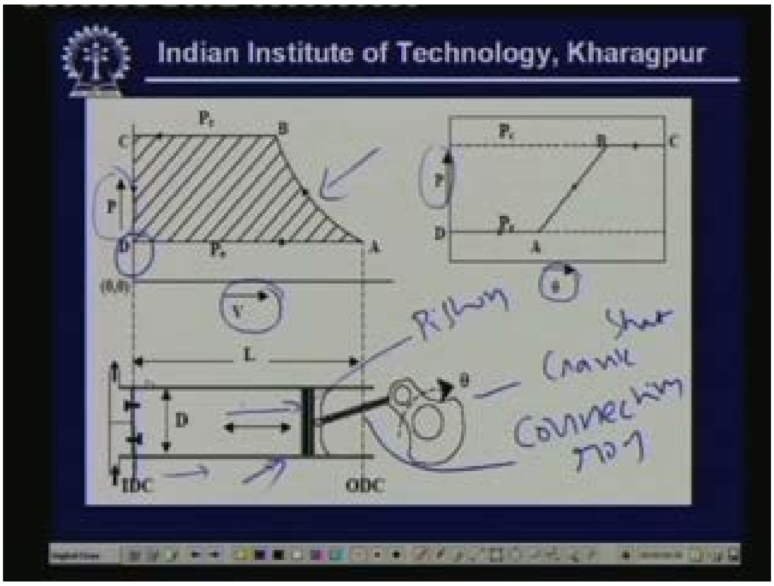

So this picture here shows the, an ideal compressor without clearance on P-V diagram okay. You can see the volume is on x-axis and pressure is on y-axis and it is also shown on P theta diagram. Theta is the crank angle P is the pressure okay. And the compressor schematic of the compressor is shown here. As I said this is the cylinder and this is the piston. And this is your connecting rod and this is the crank shaft. So as the crank shaft rotates you can see that the piston moves in this direction to and fro and this causes the suction and compression of the refrigerant gas. So since this is a compressor without any clearance when the compressor starts moving in this direction. That means from the inner dead centre IDC. There will not be any gas left in the compressor. That means the suction stroke starts right at this point okay that means at point D. So when the suction strokes starts the volume inside the cylinder is zero. That means this is what is known as a cylinder without any a compressor without any clearance okay. Let me explain the processes here.

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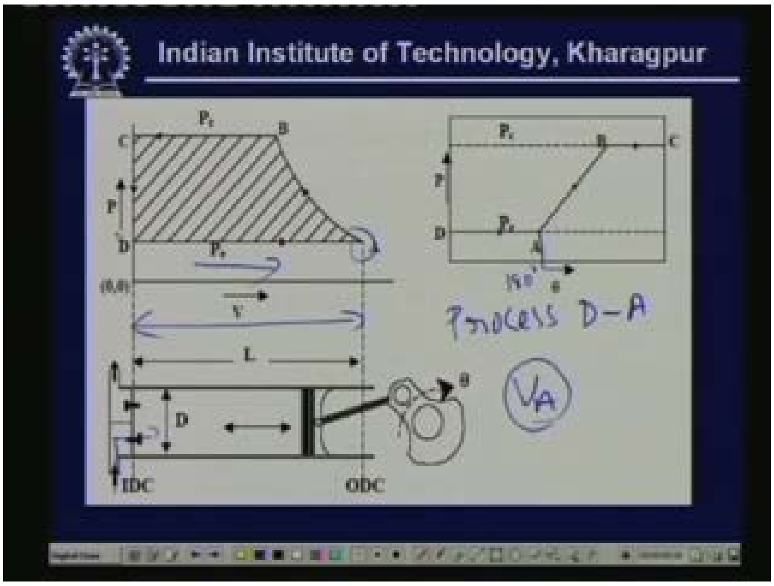

It consist of three processes first process is process D to A during this process the piston moves from the inner dead centre to the outer dead centre. So as the piston moves from the inner dead centre to the outer dead centre initially there is no refrigerant gas inside the cylinder. So when once the piston starts moving the pressure inside falls below that of the suction pressure. So as a result refrigerant vapour enters through the suction valve into the compressor. So this process continues as the piston continues to move from inner dead centre to the outer dead centre that means this process continues from D to A okay. So this is what is shown on your P theta diagram typically at this point you have an angle of one eighty degrees okay.

So this is what is known as suction stroke. So during this suction stroke what is the piston displacement piston, displacement is nothing but this okay. That means VA the volume VA and what is the volume of the gas that has entered volume of gas that has entered is also equal to VA okay. Because there is no clearance here. So no let us look at the second process that is compression process.

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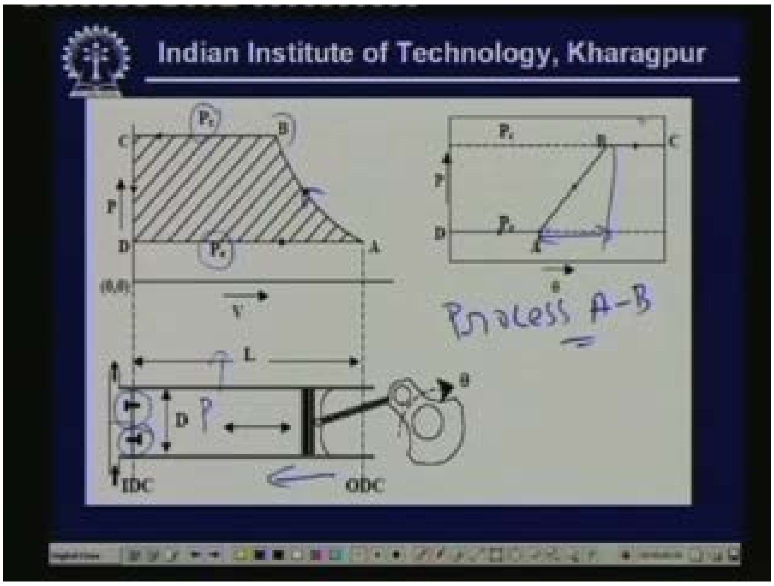

Compression process is process A to B. So during this process the piston starts moving in the opposite direction. That means from the outer dead centre to the inner dead centre. As it starts moving in the outer from outer dead centre to inner dead centre the volume of the refrigerant inside the cylinder starts decreasing. Once its starts decreasing the pressure builds up here once the pressure builds up here the suction valve will be closed okay. Because the pressure inside will be greater than the suction pressure. So the suction valve is closed and the discharge valve also remains closed. Because here the, this pressure is lower than the condensing pressure. As the result both the valves are closed so the volume gets reduced as the volume is reduced in this direction the pressure raises. So this is the typical compression process and during this process the pressure raises from the evaporator pressure Pe to the condenser pressure Pc. That means a point B okay so this is the suction process and this occupies certain crank angle okay, from A to B.

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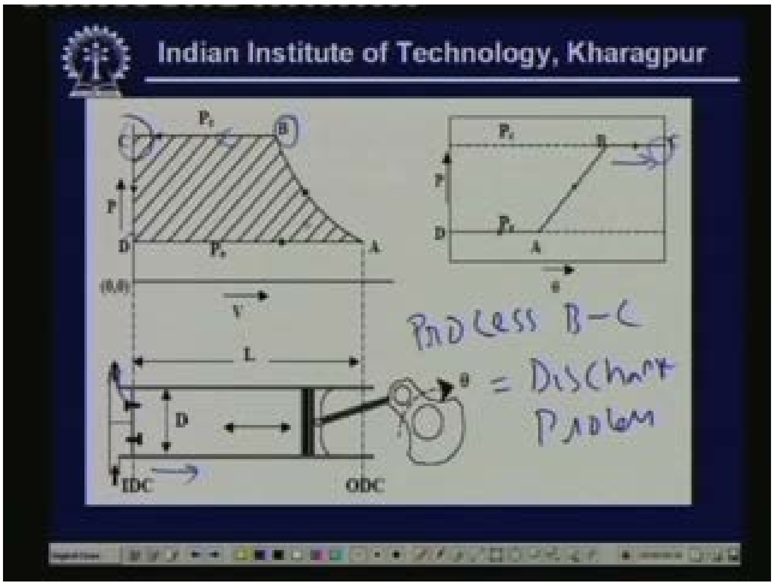

Now once the pressure reaches that of the condenser pressure since this is an ideal compressor no pressure drop is required for fluid flow. So as soon as the pressure reaches at this point further movement of the compressor from point B to C results in the opening of the discharge valve and flow of refrigerant out of the discharge valve to the compressor. That means there is at discharge of the refrigerant from the compressor to the condenser okay. That means process B to C is a discharge process okay. So during this process refrigerant at a constant pressure Tc is expelled from the cylinder and from here it goes to the condenser where it gets condensed. And this process ends as you can see at point C and at point C what is the volume of the refrigerant inside the cylinder it is zero okay. Because there is no clearance right that is at this point. So during the reverse stroke that means again the piston is at IDC and when's it when it starts moving in the opposite direction again the pressure starts falling. So the suction valve opens refrigerant fresh charge of refrigerant enters into the cylinder okay, and the cycle continues. So this is the working principle of a compressor without a clearance.

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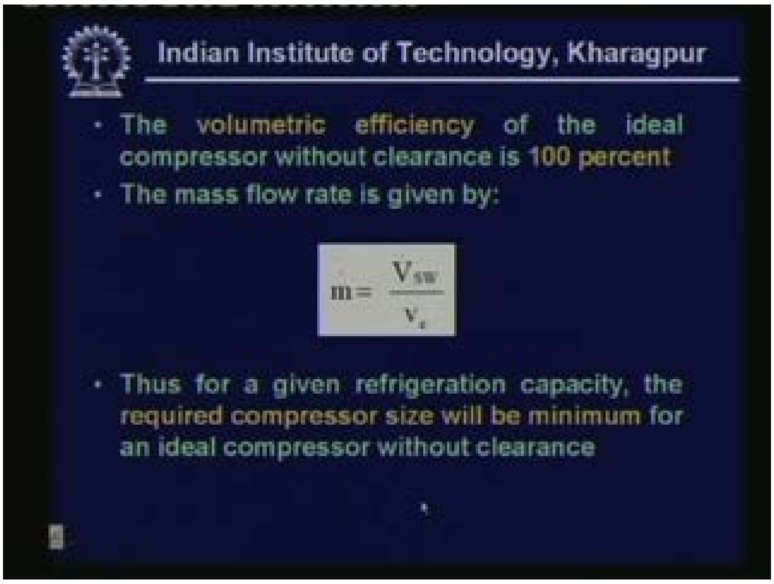

Since you can see that the volumetric displacement rate of the compressor is equal to the volume of the gas taken in the volumetric efficient of the ideal compressor without clearance is hundred percent okay. So the mass flow rate is given by m dot is equal to V dot sw where V dot sw is known as displacement rate divided by Ve Ve is the a specific volume of the refrigerant at compressor inlet okay. So from this expression you can see that for a given refrigeration capacity the required compressor size will be minimum for an ideal compressor without clearance. Because here the mass flow rate pumped will be maximum for a given size.

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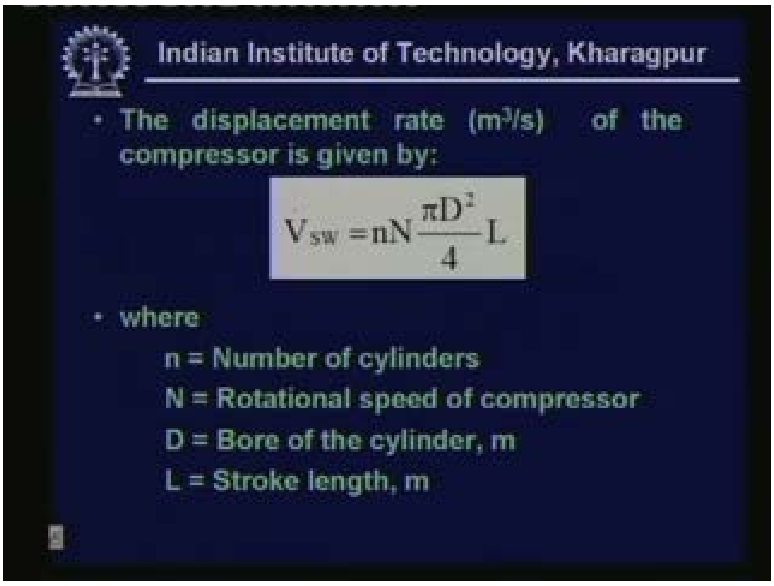

And the displacement rate in metre cube per second of the compressor is given by V dot sw is equal to n small n into capital N into pi D square by four into L where small n is a number of cylinders you can have as many as sixteen cylinders. And N capital N is rotational speed of compressor in revolutions per second. And D is the inner diameter of the cylinder or bore of the cylinder in metres and L is the stroke length in metres. So once you know the speed number of compressor number of cylinders diameter and length you can find out what is the displacement rate using this expression.

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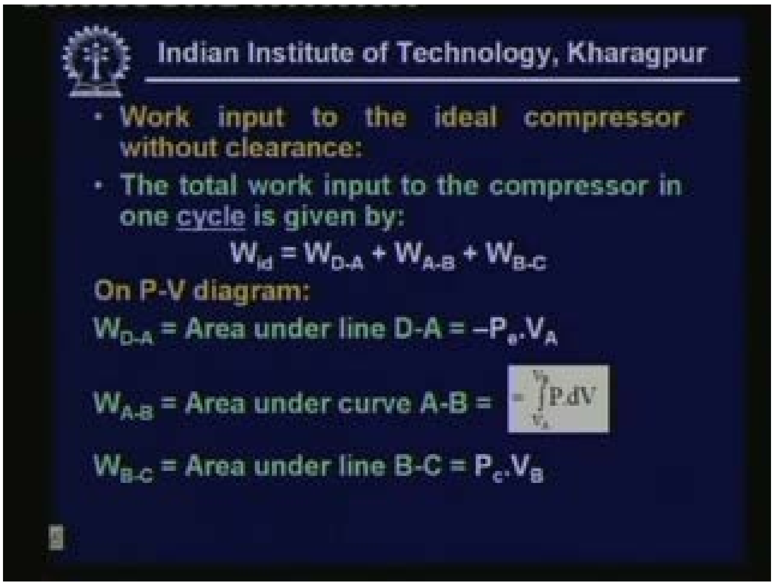

Now let us find out what is the work input to the ideal compressor because as I said important parameters are mass flow rate and work input. So work input to the ideal compressor without clearance is given by W id and here W i capital W subscript id is the total work input to the compressor in one cycle. And this is given by WDA plus WAB plus WBC what are these let me show on the cycle.

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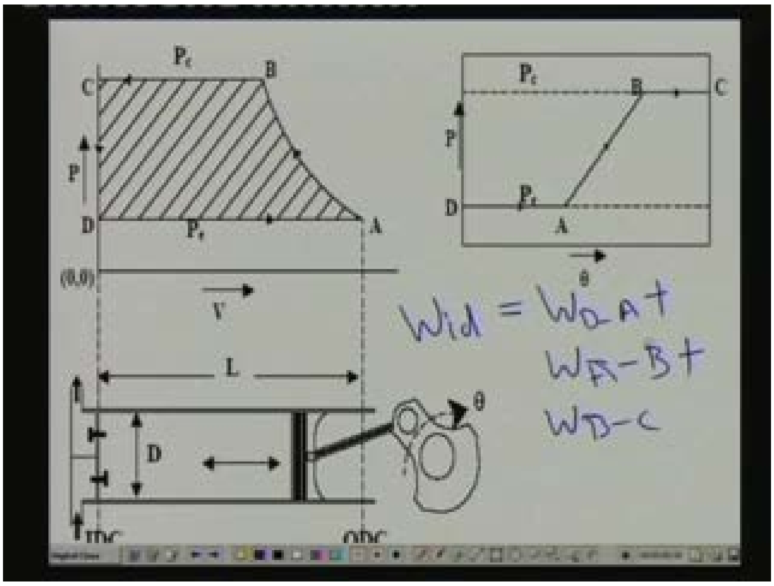

So total work input in one cycle W id is what is the work done during the process D to A plus? What is the work input to the compressor during process A to B plus? What is the work input to the compressor during process B to C okay. Because it consists of three processes. So the total work input is sum total o f all these three processes. Now let us look at these individual processes.

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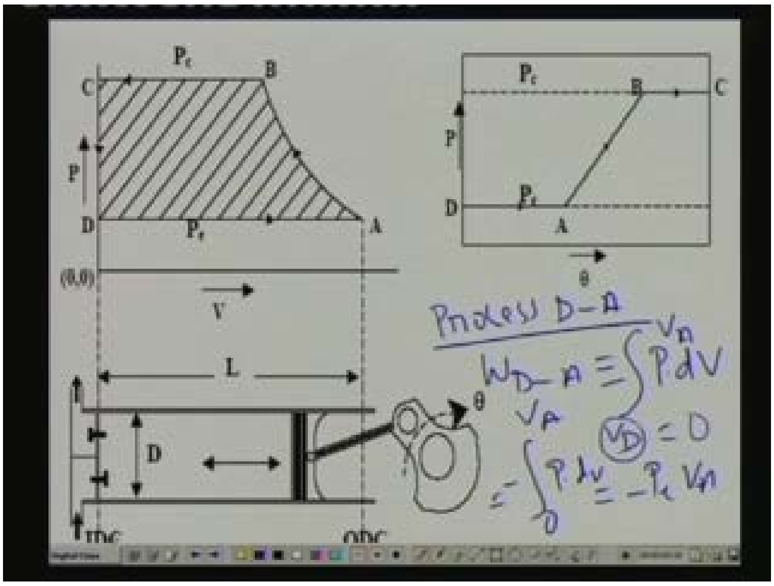

For example what is the work done during process D to A and who is doing work on what during process D to A the refrigerant does work on the piston okay. And this process takes place at constant pressure. So the work D to A is equal to integral P dv and if you are writing work output as negative then it is minus integral P dv from initial volume VD to final volume VA. Since initial volume is VD is zero so this simply becomes integral zero to VA P into dv and P is constant at P. So simply is equal to minus Pe into VA okay. So this is the work output actually because if you consider refrigerant as the system is doing work on the piston okay. So you have the negative sign here.

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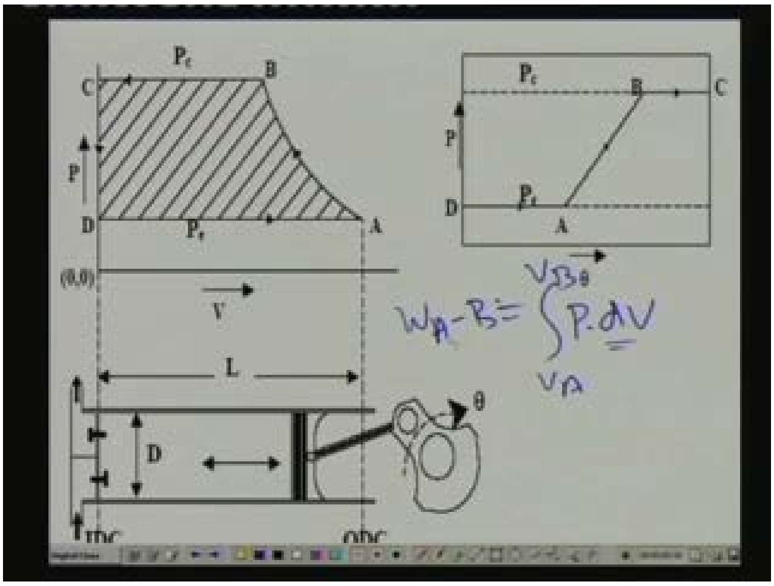

Now what is the work input to the system during the compression process that is during process A to B. During this process ah again the, this is equal to integral P dv because this is the closed system from VA to VB okay. And this is the work input to the system because dv is ah negative so system piston has to do work on the refrigerant okay. You cannot integrate this simply because you do you have to in order to perform this integration you have to know what is the relationship between P and V during this process okay.

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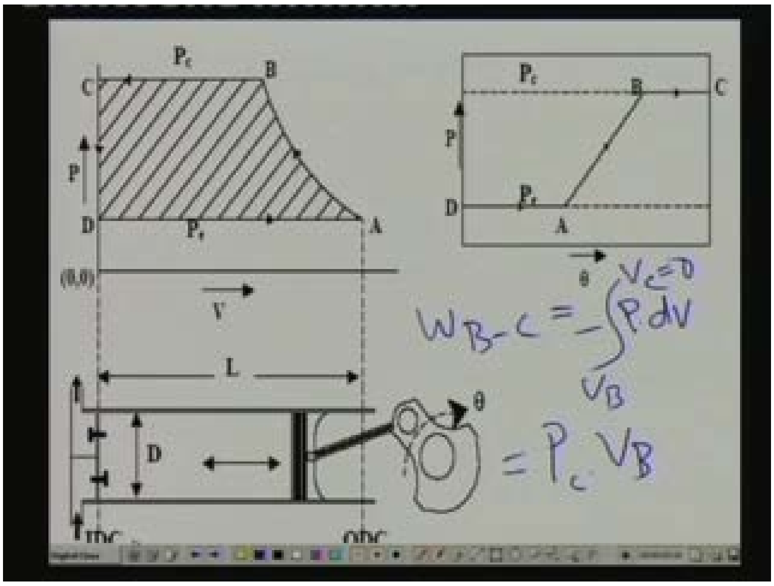

And finally let us look at what is the work input during process B to C this is an isobaric process. So simply this is equal to integral ah P dv from VB to VC okay. Since this is a work input if you are using negative. Then this is simply equal to pressure is constant here. This is equal to Pc into VB because VC is equal to zero okay. So that is why you can find out the work input during each process.

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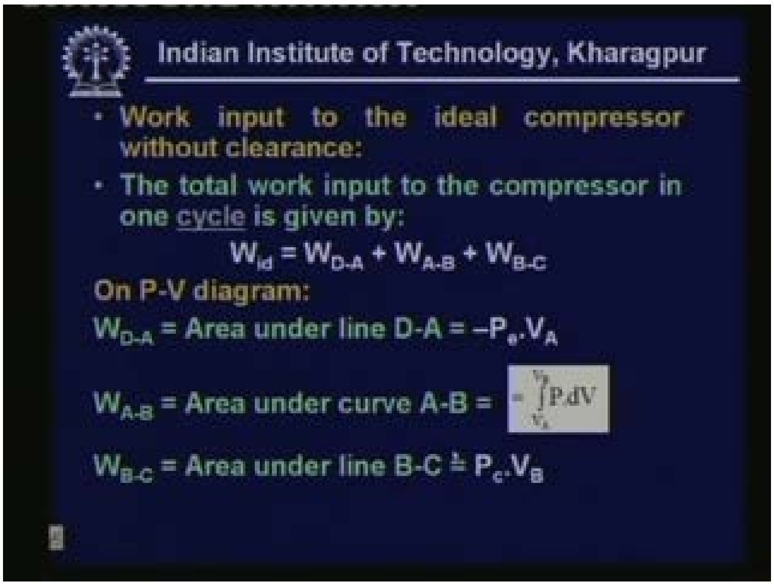

So that is what is shown here on P-V diagram W DA is area under line D-A okay. So this is equal to minus Pe into VA and W A-B. I am using the sine convention here. Since I am calling this as work input the output becomes negative okay. So that is the convention used here. So W D-A is the work output from the system so this becomes negative okay. So minus Pe into VA so W A-B is the area under curve A-B which is equal to integral P dv from VA to VB and W B-C is area under line B-C that is equal to Pc into VB okay.

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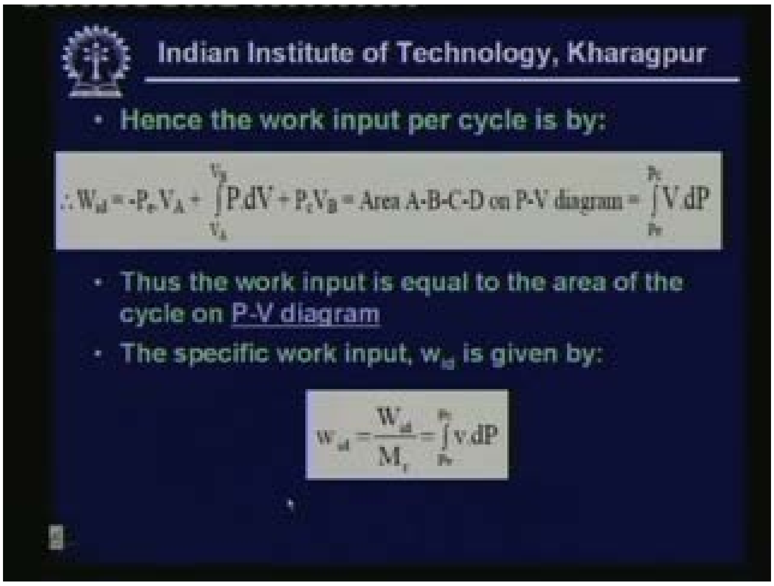

So the total work input per cycle is given by sum total of all these work inputs that is minus Pe into VA plus integral P dv from VA to VB plus Pc into VB. So this is nothing but area A-B-C-D on P-V diagram okay. So thus the work input is equal to the area of the cycle on P-V diagram which is, which can be shown to be equal to integral V dP from Pe to Pc okay, that means on the P-V diagram.

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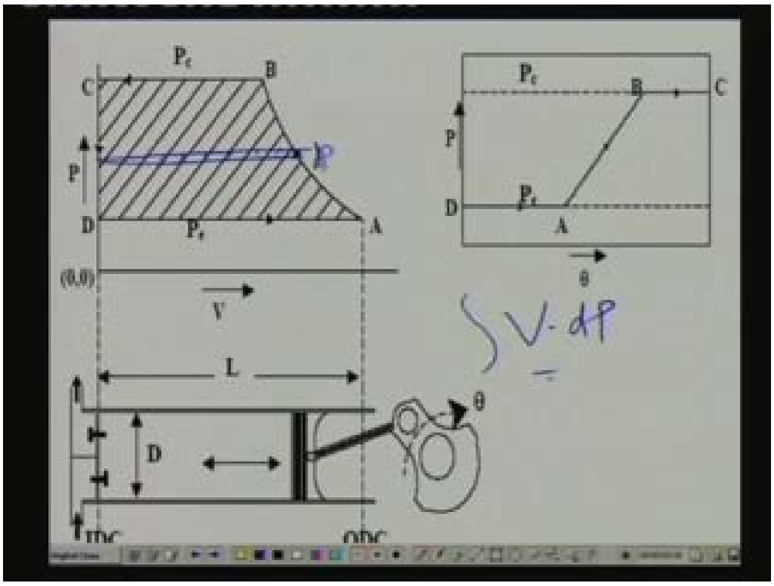

This is the, this hatched area so this is the total work input okay. So this can be obtained by integrating integral V dP okay. That means you take a small element at pressure p and integrate it from this volume to this volume okay. That means ah this becomes integral V dP this is dP okay.

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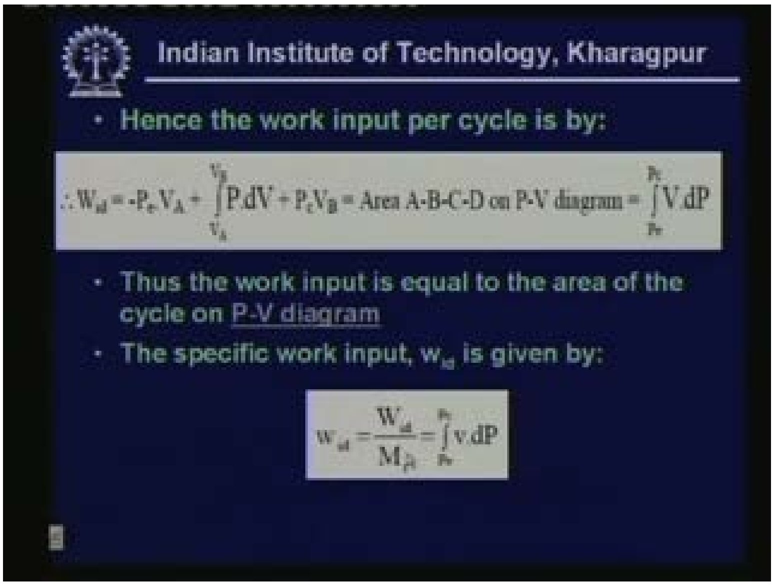

So the now the specific work input specific work input is nothing but work input to the system per kilogram of the refrigerant that means in kilo joule per kilogram. So this is given by work input per cycle divided by the mass of refrigerant compressed in cycle that is capital

M subscript r. So this is equal to W iv divided by capital MR which is equal to integral V dP where this small v is a specific volume of the refrigerant. And this integration has to be performed from Pe to PC for the compression process.

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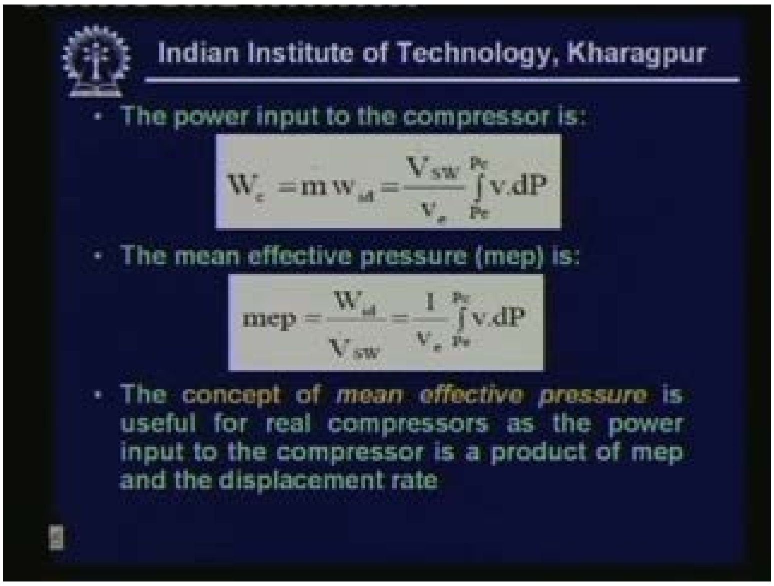

Now the power input to the compressor is nothing but mass flow rate of the refrigerant m dot into W id where W id is the specific work input in kilo joule per kilogram. So the product of these two will you a power input to the compressor. So this is equal to this can be written mass flow rate is written in terms of the displacement rate V dot sw and specific volume okay. Because m dot is equal to V dot sw divided by Ve and W id is integral ah V dP where V is the specific volume okay. And we can also define what is known as a mean effective pressure mep and mep is defined as the power input to the compressor divided by the displacement rate okay. So this should have been a this is a Wc, this is the power input to the compressor divided by displacement rate V dot sw okay. So from the above expression this is nothing but integral V dP divided by specific volume of the refrigerant at the compressor inlet.

And the concept of mean effective pressure is quite useful for real compressors. Because the power input to the compressor is the product of mep and the displacement rate. That means if you know the mean effective pressure for a real compressor. Then if you want to know the power input to the compressor all that you have to do is you have to multiply the mean effective pressure with the compressor displacement rate. And as you know the compressor displacement rate depends upon the number of cylinders rotational speed of the compressor and the compressor dimensions which are typically known okay. So you can easily calculate the power input to the compressor from the mean effective pressure, all right.

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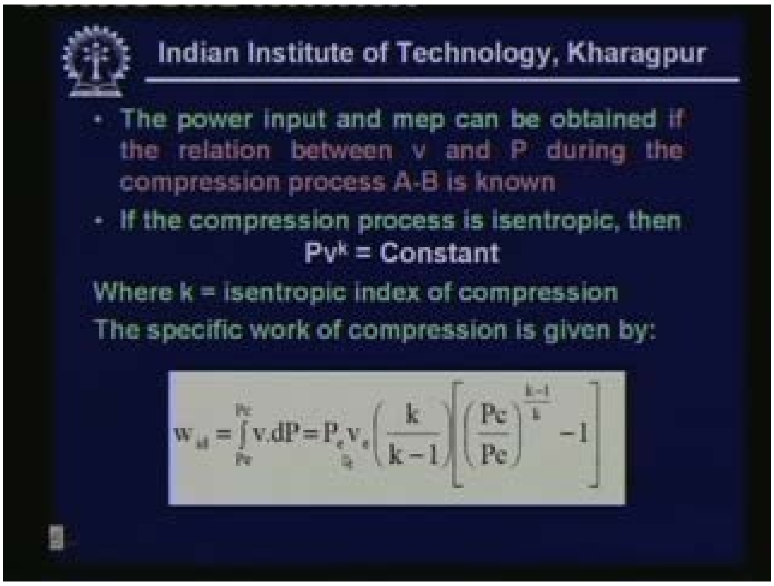

Now the, you from the expression you can see that the power input and mean effective pressure can be obtain. If the relationship between specific volume and pressure during the compression process A-B are known okay. If the compression process is isentropic then we know that, this process can be represented by the equation Pv to the power of K is constant where K is isentropic index of compression okay. As you have seen W id that is specific work of compression is integral V dP okay. So as I have already mentioned if you want to perform this integration you have to know what is the relationship between V and P during the compression process okay.

So the compression process can be anything it can be isothermal. It can be isentropic, it can be polytrophic right. And the relationship between V and P varies depending upon the type of the process. If the for the ideal compressor we assume this process to be reversible adiabatic that means the process to be isentropic. If it is an isentropic process we know from our basic thermodynamics that the process follows the equation Pv to the power of k is constant where k is known as isentropic index of compression okay. So once you know that this relation you can easily perform the integration okay. So that is what is done here.

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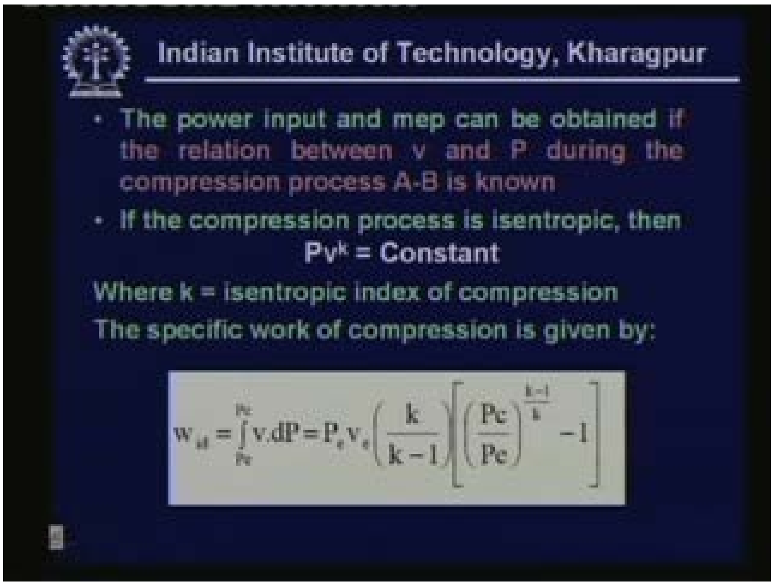

You substitute this expression Pv to the power of k in the expression for specific work of compression. From this you can show that the specific work of compression after integration is given by, so here you are substituting this expression Pv to the power of k is constant. So if you are substituting you get this expression okay. So as you know these, in this expression Pe is the suction pressure Ve is the specific volume of the refrigerant at suction condition k is a isentropic index of compression and Pc is the condenser pressure okay. So if you know these things you can find out the specific work of compression. This expression is valid for any reversible process if with the process is not isentropic but some polytrophic with an index of compression n all that you have to do is replace k by n okay. Why do we say that this expression is valid for reversible process? Because for a reversible process the process path is known that means you know the exact relationship between v and P during the process. Once you know the process path you can perform the integration that is why this expression is valid for any reversible process.

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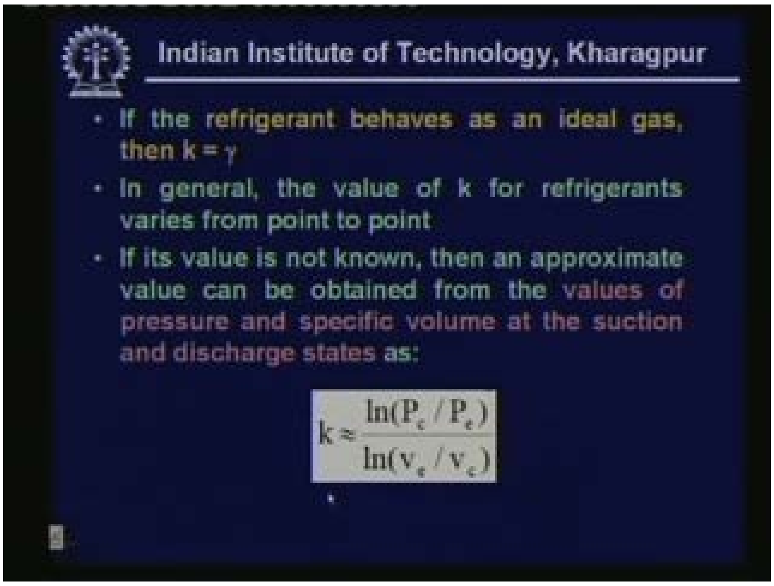

So if the refrigerant behaves as an ideal gas we know that index of compression is nothing but specific heat ratio gamma okay. But however in general for most of the refrigerants the value of k is different from value of gamma. And this value varies from point to point. And if this value is not known then an approximate value can be obtain from the values of pressure and specific volume at the suction and discharge states. That means let us say we know the suction pressure and suction specific volume. And we also know the suction discharge pressure and discharge specific volume and we know that the process follows the path Pv to the power of k is constant. Using these information we can find out the approximate value of k which is equal to a natural log of Pc divided by Pe divided by natural log of Ve divided by Vc where Pc and Pe are condenser. And evaporator pressures and Ve and Vc are evaporator specific volume at the inlet to the compressor and specific volume at the outlet of the compressor.

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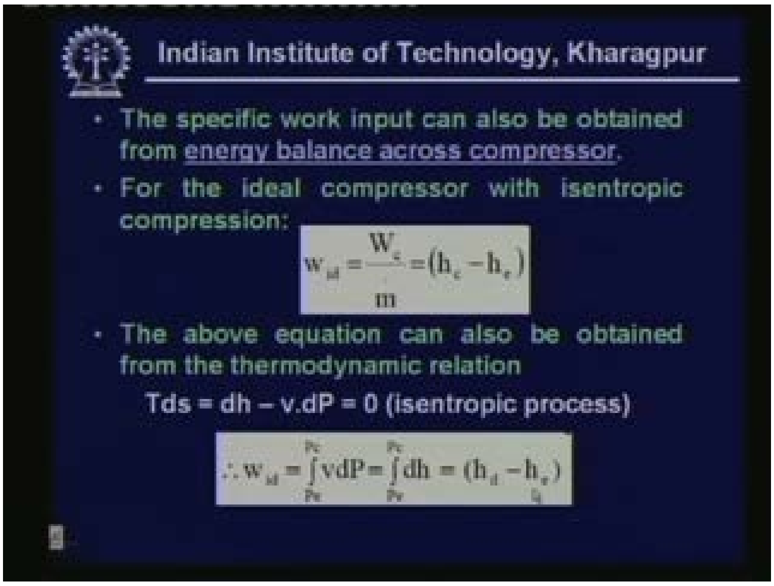

The specific work input can also be obtained from energy balance across the compressor okay. You can also perform energy balance and you can find out the specific work input what do you mean by energy balance.

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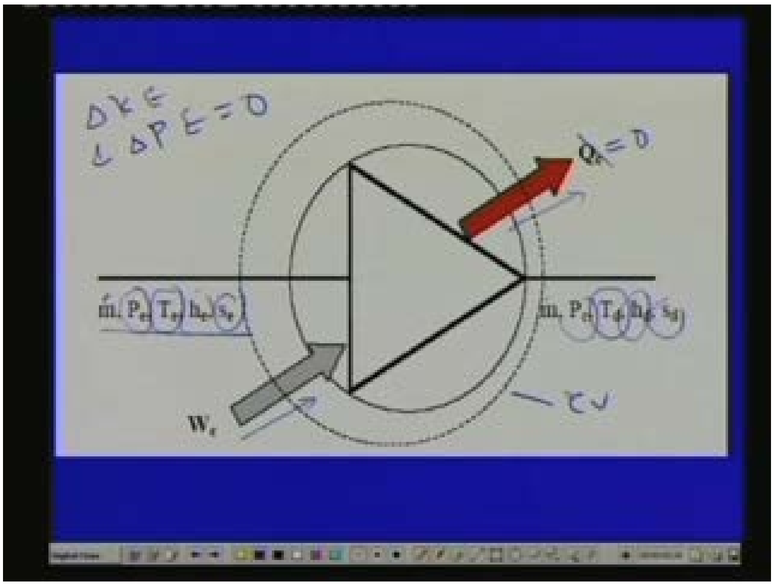

That means you can have, let us say that, this is the compressor and this is the inlet condition where m dot is the mass flow rate. Since this is the steady we are assuming this to be a steady flow this thing. So mass flow rate inlet mass flow rate as same as outlet mass flow rate and these are the inlet condition inlet pressure Pe inlet temperature Te inlet enthalpy he and inlet entropy se. And outlet conditions pressure Pc discharge temperature Td discharge enthalpy hd and discharge entropy sd okay. And you have a net amount of work input Wc is supplied to the compressor and a net amount of heat transfer Qc takes place from the compressor to the surroundings for reversible adiabatic is this is equal to zero okay. And if you assume that delta KE and delta PE that is kinetic and potential energy changes across the control volume are negligible.

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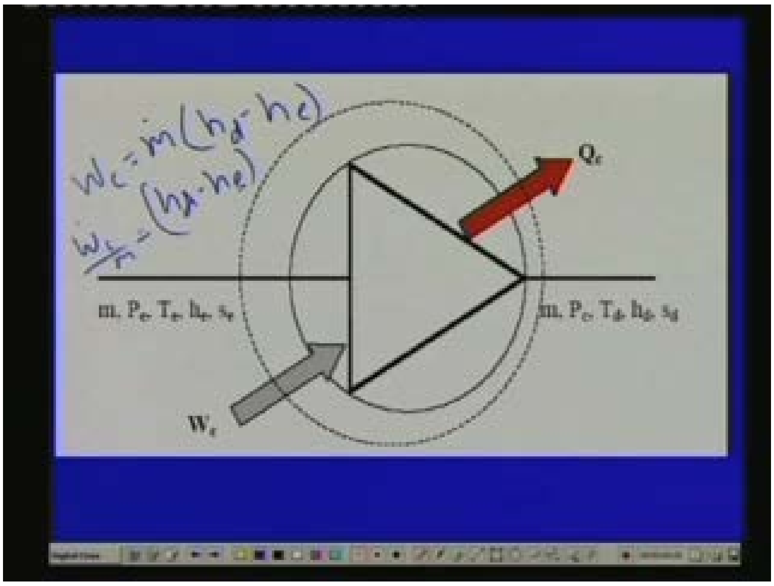

Then you can easily apply the energy balance energy coming in is equal to energy going out or Wc is equal to mass flow rate into hd minus he or specific work of compression W c by m dot is equal to hd minus he. That means if you know the exit and inlet enthalpies you can easily find out the specific work input to the compressor okay. That is what is shown here W id is equal to okay, this is hd minus he okay.

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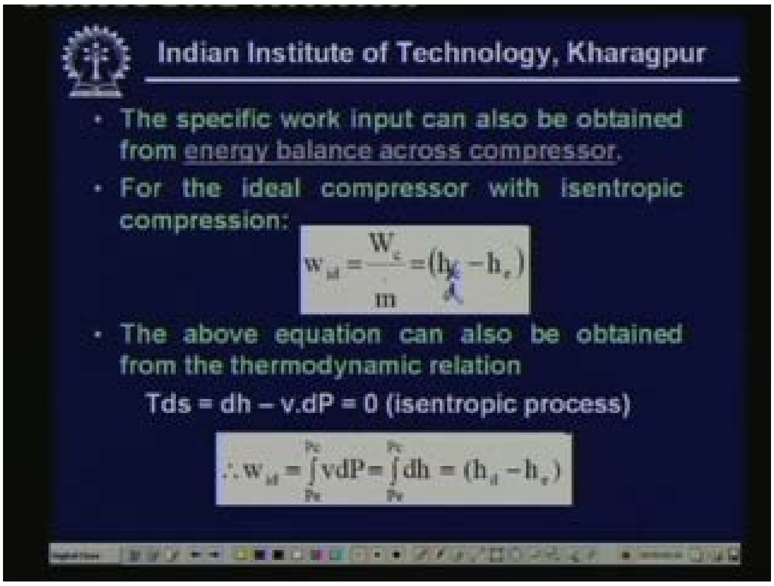

The above equation can also be obtained from the thermodynamic relation Tds is equal to fh minus v dP okay. This relationship is valid for both reversible as well as irreversible processes but for as isentropic process we know that ds is equal to zero. That means dh is equal to v dP for an isentropic compression process and W id. That is the specific work input is nothing but integral vdP and for this special case of isentropic process vdP is equal to dh. So integral vdP is equal to integral dh from Pe to Pc since dh is a property simply you can write this as integral dh is equal to hd minus he that is exit and inlet enthalpies of the refrigerant okay. Remember that, this is only for an isentropic process. That means there is no heat transfer from the compressor if there is a heat transfer the expression will be different.

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Now let us look at an so far we have been discussing an ideal compressor without clearance. That means the suction strokes starts with zero refrigerant inside the cylinder okay. And in actual compressors this is not possible okay. Some amount of clearance has got to be provided in actual compressors. So what we do is we eliminate the assumption of no clearance okay. Still we wil,l we are discussing ideal compressors only. So now let us look at ideal compressors with clearance first of all why do we need clearance?

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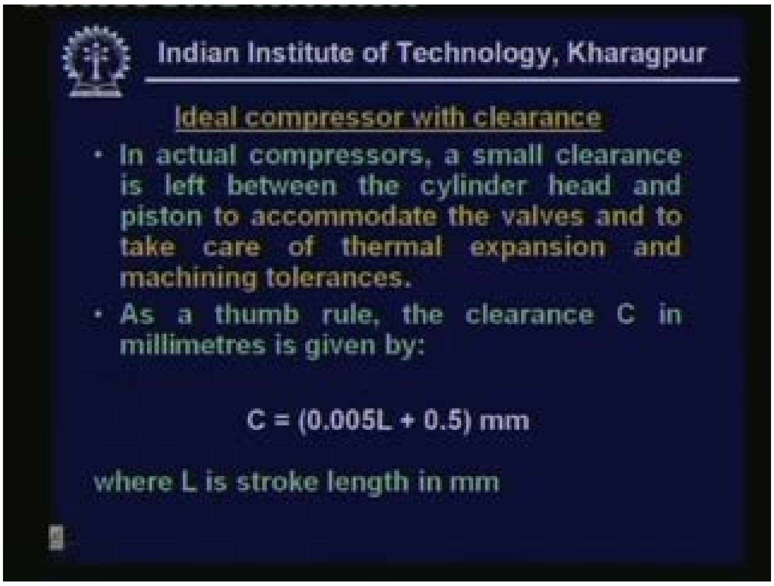

In actual compressors a small clearance is left between the cylinder head and piston to accommodate the valves and to take care of thermal expansion and machining tolerances okay. If you do not provide any clearance then due to tolerances or thermal expansion there could be problem okay. Also you have to accommodate the valves. So you have to provide some gap between the cylinder head and the piston. And as a thumb rule the clearance C in millimetres is given by C is equal to point zero zero five L plus point five and C is written. As I said in millimetres and here L is the stroke length in millimetres this a generally a thumb rule.

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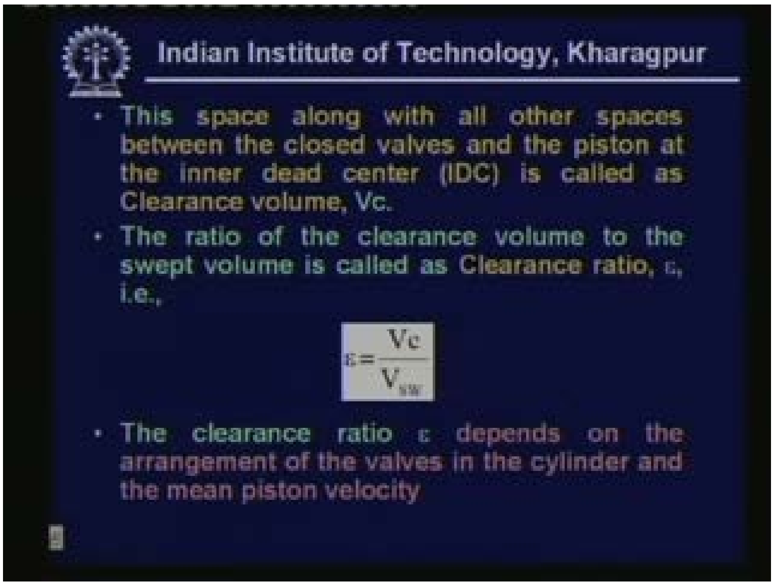

And this space along with all other spaces between the closed valves and the piston at the inner dead centre is called as the clearance volume okay. So clearance volume is not just the space between the closed valve and the piston but all other spaces when valves are closed okay. So all these spaces are known as clearance volume Vc and the ratio of the clearance volume to the swept c volume is called as clearance ratio epsilon. That means epsilon is defined as Vc divided by V sw where V sw is the swept volume of the compressor. That is number of cylinders into pi d square by four L okay, in metre cube and the clearance ratio epsilon depends on the arrangement of the valves in the cylinder. And the mean piston velocity and this value can vary anywhere between four to twelve to thirteen percent.

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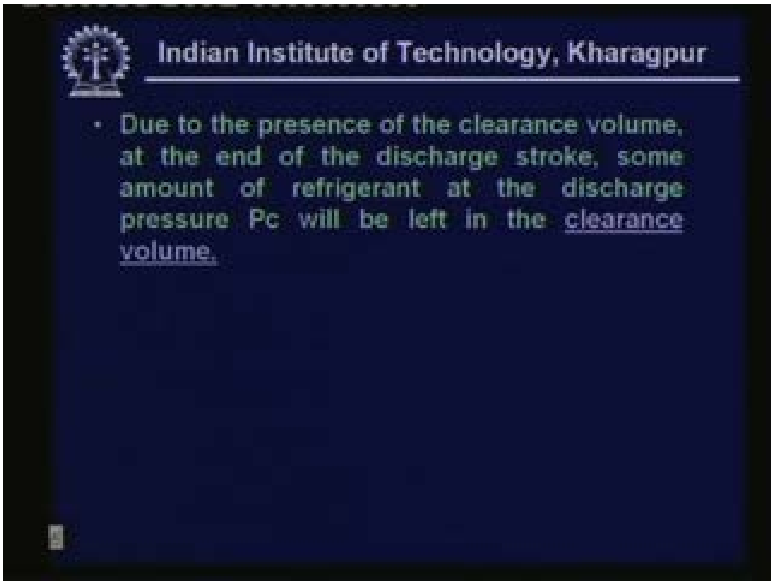

Due to the presence of the clearance volume at the end of the discharge stroke some amount of refrigerant at the discharge pressure Pc will be left in the clearance volume okay.

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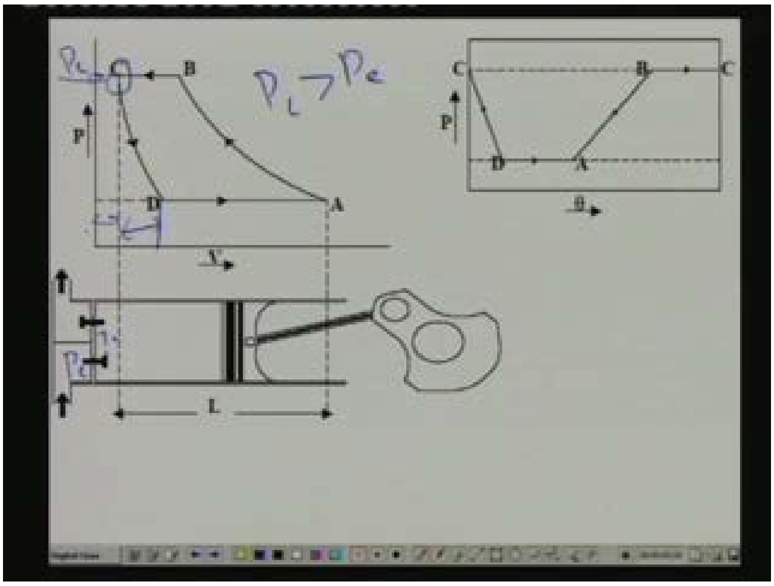

So what happens is, because of this clearance this discharge does not go up to this point but it stops at some point C okay. So some volume is left at this point and at this point the return strokes starts. So at this point you can see that the pressure is Pc which is much greater than pressure Pe. That means pressure at this point is Pe and pressure at this at the beginning of the suction stroke is Pc. Since Pc is greater than Pe this valve cannot open okay. So a part of this suction stroke is simply utilised for reducing the pressure from Pc to Pe. That means this is the portion which is used for reducing the pressure from Pc to Pe okay. So the suction valve opens only when the pressure falls to the evaporator pressure Pe okay.

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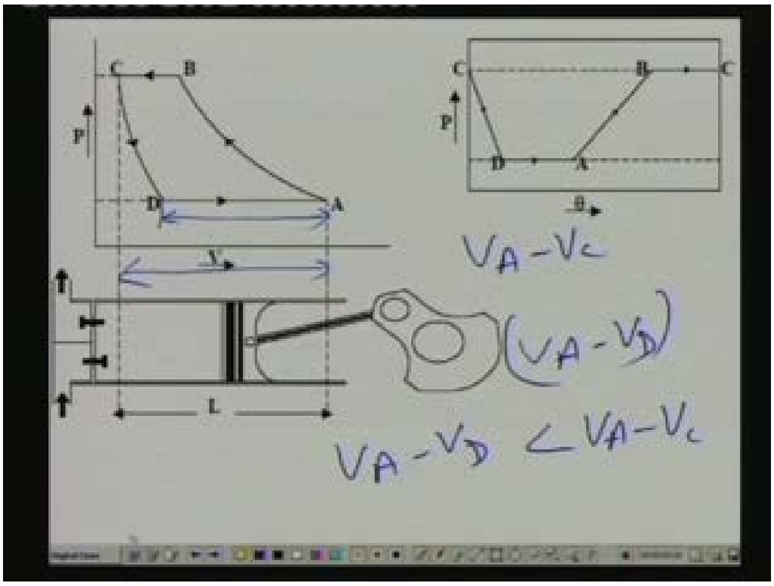

So what is the net effect of this the net effect of this, from this is, that this is the piston displacement okay. That means VA minus VC is the piston displacement but the actual volume of refrigerant the, that has entered into the cylinder is VA minus VD okay. And you can see from this figure that VA minus VD is less than VA minus VC right. That means the displacement rate is higher than the volumetric flow rate of the refrigerant. That means the volumetric efficiency of the compressor is less than hundred percent okay.

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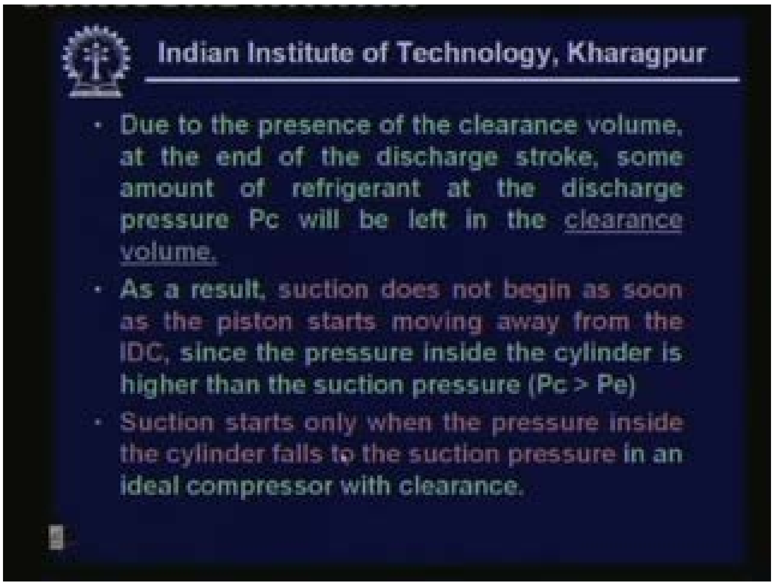

That is what is mentioned here.

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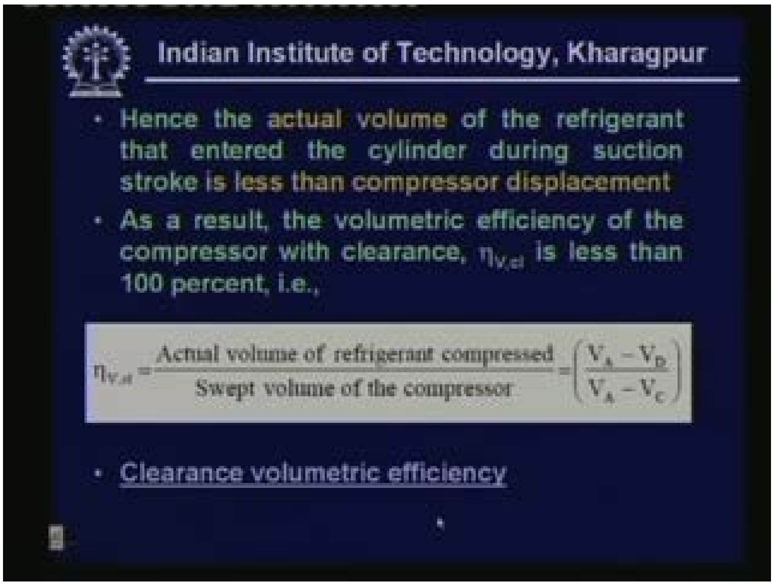

So hence the actual volume of the refrigerant take a, that entered the cylinder during suction stroke is less than compressor displacement. As a result the volumetric efficiency of the compressor with clearance is less than hundred percent. And this is defined as VA minus VD divided by VA minus VC okay. So that is I have already explained.

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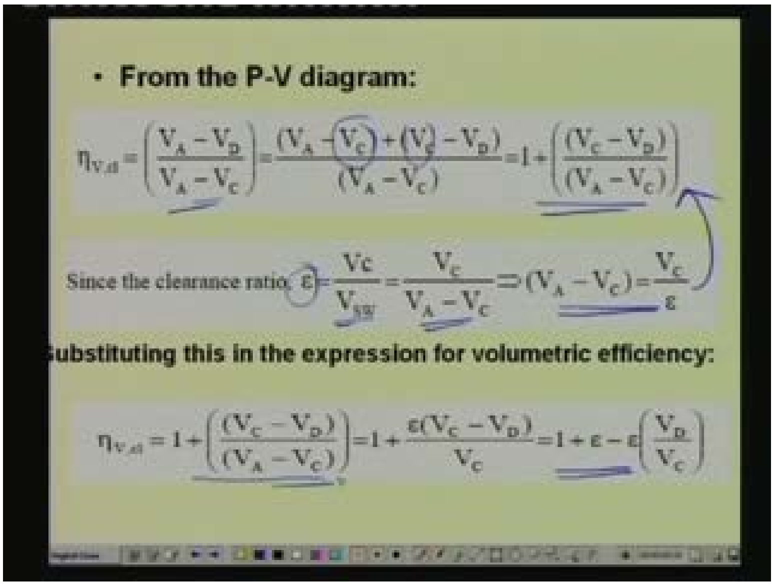

And let us try to find an expression for this. So volumetric efficiencies for this condition is VA by VD VA minus VD divided by VA minus VC. Now let us subtract and add VC okay. So let us write this as VA minus VC plus VC minus VD divided by VA minus VC which is equal to one plus VC minus VD divided by VA minus VC. Now the clearance ratio epsilon is defined as VC by V swept that is, swept volume and swept volume in this case is nothing but VA minus VC okay. So from this expression VA minus Vc is written as Vc divided by epsilon okay. If you substitute this in this expression you can show that the clearance volumetric efficiency is nothing but one plus VC minus VD divided by VA minus VC that is finally equal to one plus epsilon minus epsilon into VD by VC.

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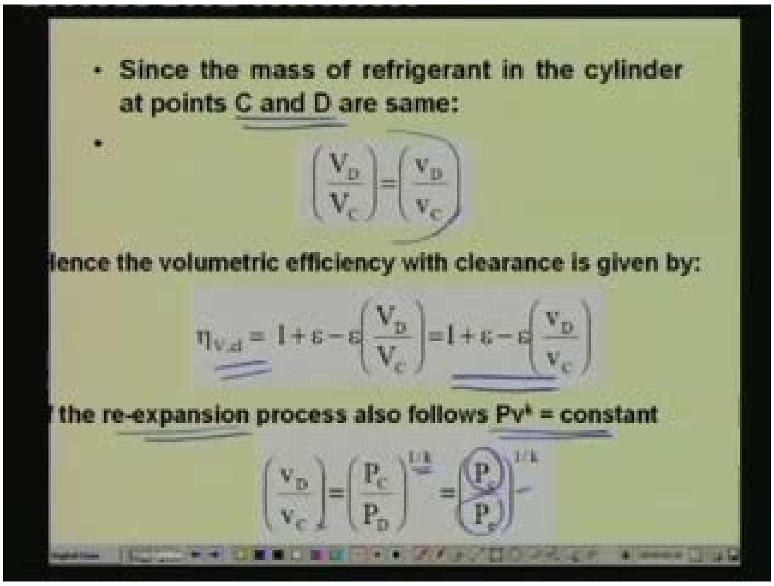

Since the mass of refrigerant in the cylinders at points C and D that means at the beginning of the suction stroke are same. You can write this expression. That means you can express the volumes in terms of specific volumes okay, VD by VC in terms of specific volume ratio small VD by small VC okay. That means clearance volumetric efficiency can be written in terms of specific volume ratio okay. And if the re-expansion process also follows Pv to the power of k is constant then you can write for the re-expansion process. This expression that means VD by VC is equal to PC by PD to the power of one by k which is nothing but Pc by Pe to the power of one by k where Pc is the condenser pressure and Pe is the evaporator pressure.

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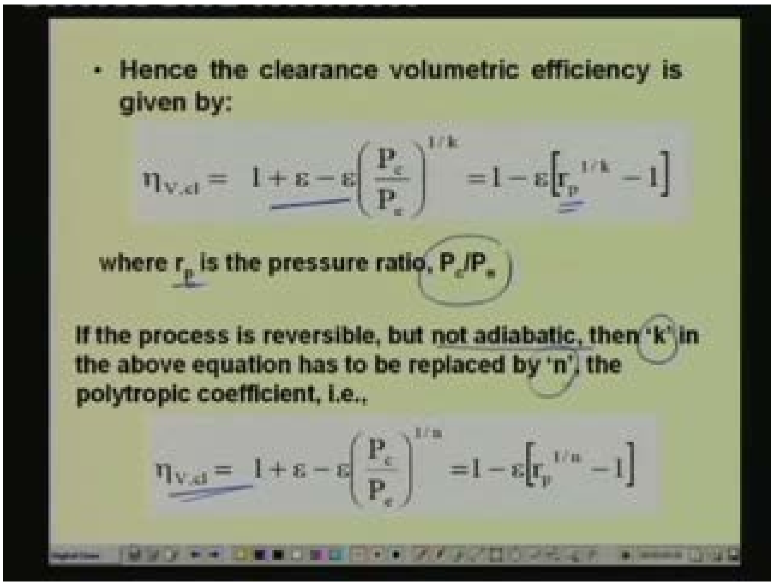

So finally you find that the clearance volumetric efficiency is simply given by one plus epsilon minus epsilon into Pc by Pe to the power of one by k or this can also be written in terms of pressure ratio rp which is nothing but the ratio of condenser pressure divided by the evaporator pressure. And if the process is reversible as I have already explained but not adiabatic then k has t o be replaced by a polytrophic index n okay. So with for any reversible process this is the expression for clearance volumetric efficiency okay.

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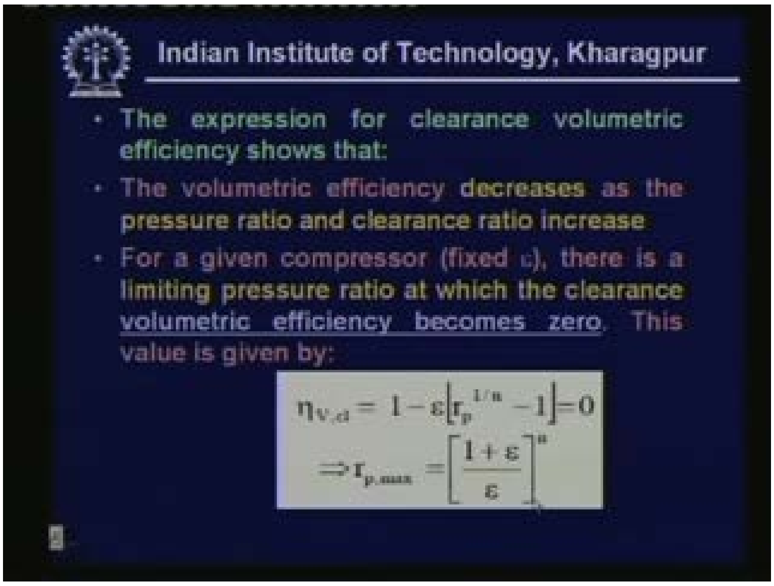

So the front he expression for clearance volumetric efficiency we can deduce that the volumetric efficiency decreases as the pressure ratio and clearance ratio increase okay. And for a given compressor that means for a fixed clearance ratio epsilon there is a limiting pressure ratio at which the clearance volumetric efficiency becomes zero okay. This is this value is given by this expression and the rp maximum at which the clearance volumetric efficiency becomes zero is simply equal to one plus epsilon divided by epsilon to the power of n okay. That is basically obtained by equating the expression for the volumetric ratio to zero okay.

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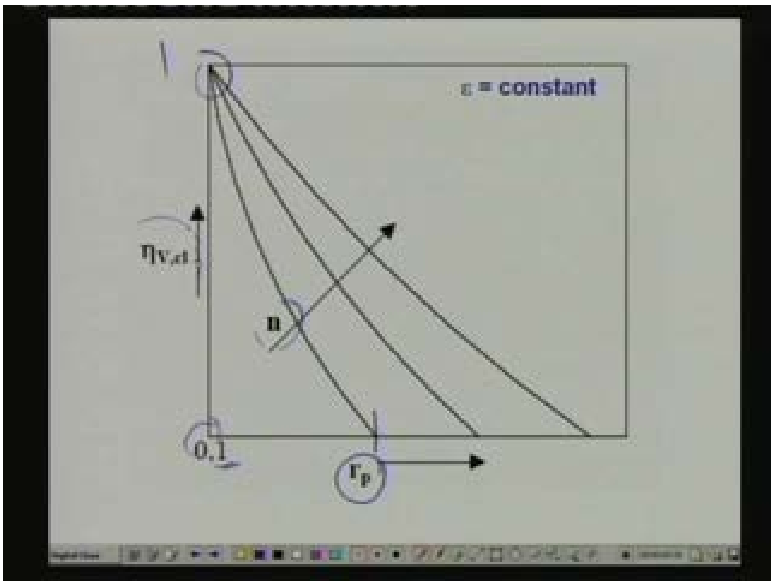

This is also shown in this figure okay. So if you are plotting the volumetric clearance volumetric efficiency versus a pressure ratio for different values of index of compression okay. You get this kind of curve here the efficiency is zero and here the efficiency is one and the rp varies from a value of one to some value okay. And at this point that in that means this n at this limiting value of rp the volumetric efficiency becomes zero.

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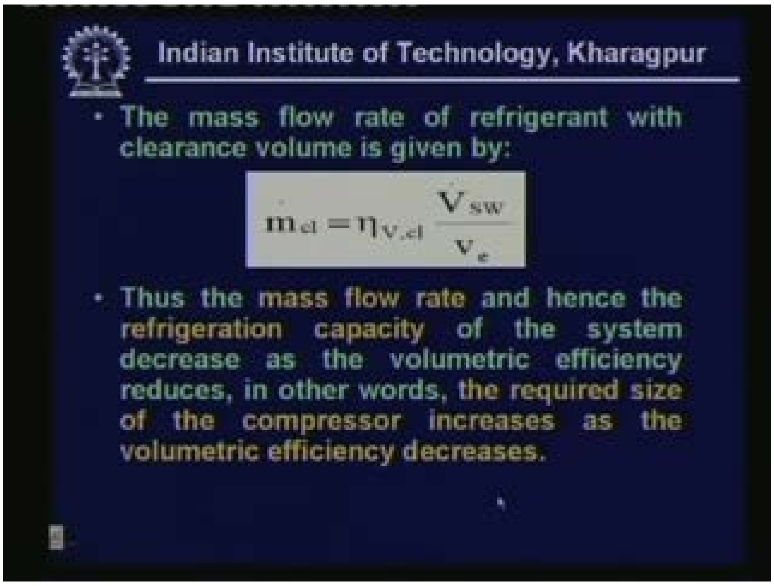

And the mass flow rate of refrigerant with clearance volume is simply equal to m dot cl is equal to displacement rate of the compressor into volumetric efficiency. That is eta V cl into displacement rate divided by specific volume of the refrigerant at compressor inlet. So a from this expression you can see that the volumetric efficiency is less than one. That means the mass flow rate and hence the refrigeration capacity of the system decrease as the volumetric flow efficiency reduces. In other words the required size of the compressor increases as the volumetric efficiency decreases.

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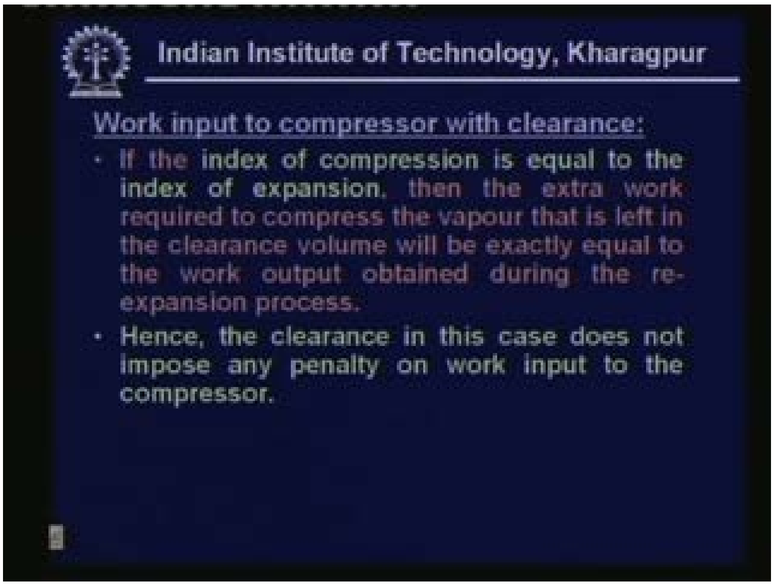

Now let us quickly look at the work input to compressor with clearance if the index of compression is equal to the index of expansion. Then the extra work required to compress the vapour that is left in the clearance volume will be exactly equal to the in output obtained during the re-expansion process. That means the work input during the compression process will be exactly equal to the work output during the re-expansion process. That means clearance does not play any role in the work input and there is no penalty because of this. Hence the total work input to the compressor during one cycle will then be equal to the area of the cycle diagram on P-V diagram okay.

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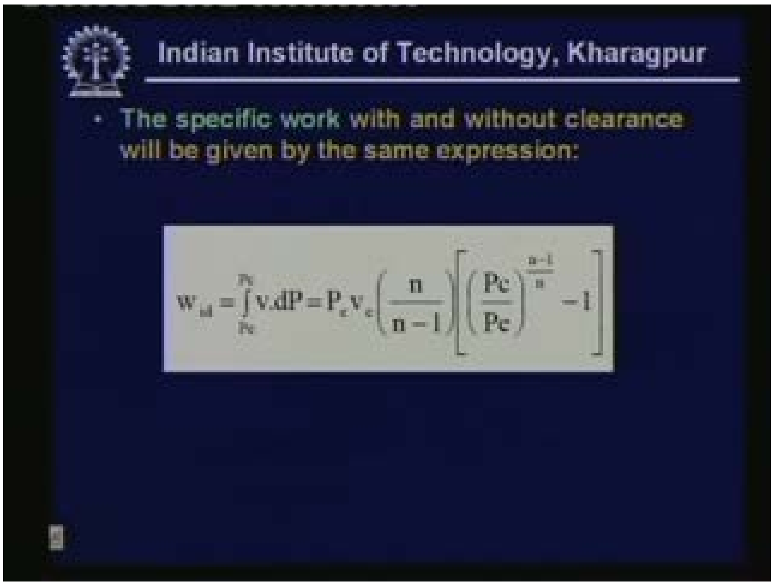

And the specific work with and without clearance will be given by the same expression okay. So the expression remains same whether for expression for specific work remains same whether compression taking place with or without clearance.

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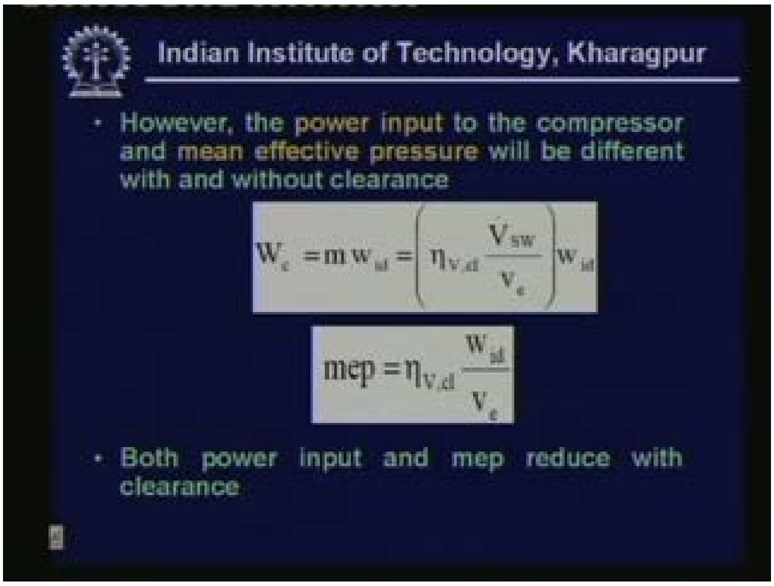

However the power input to the compressor and mean effective pressure will be different with and without clearance because the mass flow rate is different okay. So even the specific work input remains same work input and mep will be different and that is given by these expressions okay. A power input is m dot into w id so where the clearance volumetric efficiency is coming into picture. Similarly for mep and you can see that both power input and mep reduce with clearance okay.

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So let me quickly sum up what we have discussed in this lesson. In this lecture the following topics were discussed classification of refrigerant compressors open and hermetic compressors ideal compressor without clearance. And its performance characteristics ideal compressor with clearance and its performance characteristics. And the performance and design aspects of reciprocating compressors will be discussed. In the next lecture and let me give the answer to the homework problem in given in the last class.

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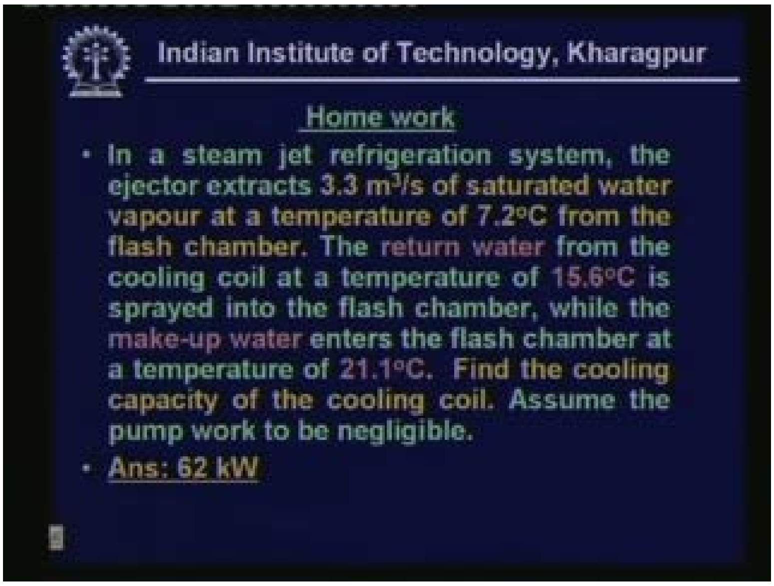

The answer to this problem is sixty-two kilo watts okay, thank you.