Applied Thermodynamics
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Module - 06
Reciprocating Air Compressor
Lecture - 43
Reciprocating Compressor - Analysis and Modelling

Dear learners, greetings from IIT, Guwahati. We are in the Applied Thermodynamics. So today, we are going to start a new module that is module 6, and the name of this module is Reciprocating Air Compressors.

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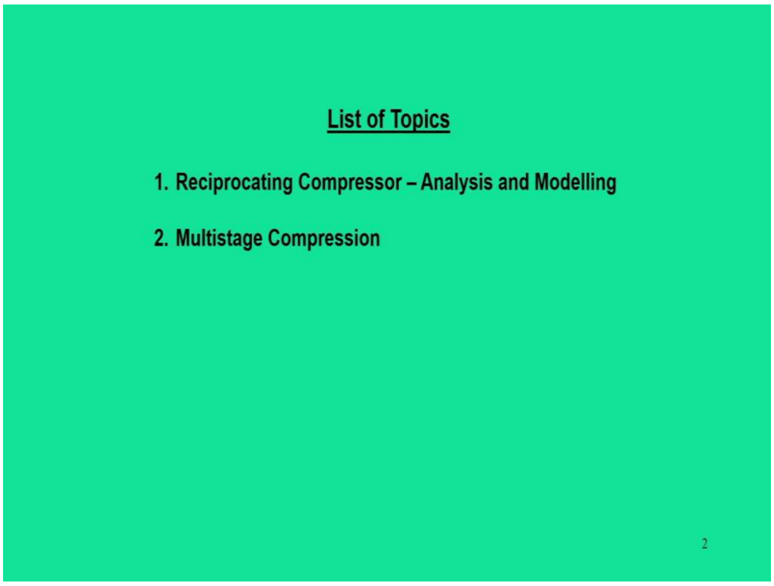

Under this module, we have two lectures, mainly the first one is the reciprocating compressor and it will be a single stage compressor for which we will discuss about thermodynamic analysis and modelling. Then, in the next lecture we will have multistage compression. So, these two topics will constitute, this module 6.

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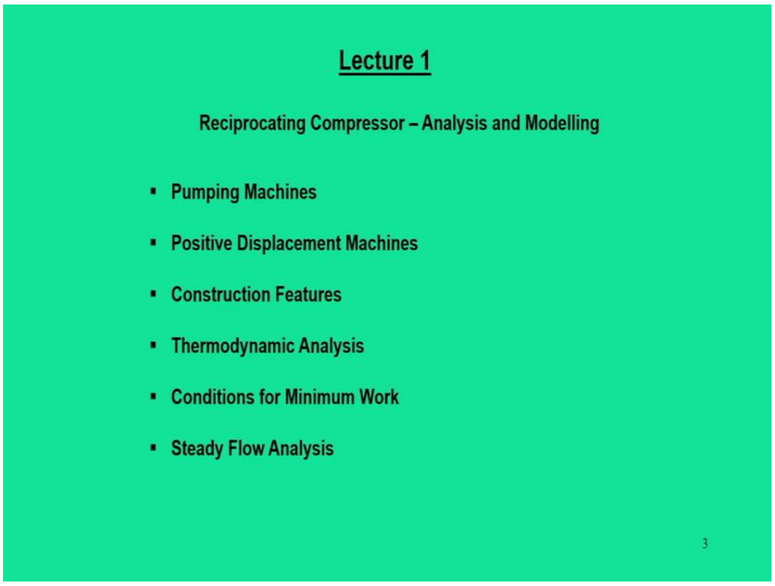

Now, on the first lecture that is the Reciprocating Compressor Analysis and Modelling. Today, we will be dealing with the following segments. First we will try to introduce pumping machines and positive displacement machines, under this headings where this reciprocating compressor is going to fit.

And a, for a simple compressor we will discuss about its construction feature and working principle. Subsequently, we will do the thermodynamic analysis, that means, how much power is required to run this compressors for a given pressure ratio.

And what is the conditions for minimum work means that an ideal reciprocating compressor would be one which will consume minimum work. And finally, we will do some steady flow analysis based on the thermodynamic equations we have studied.

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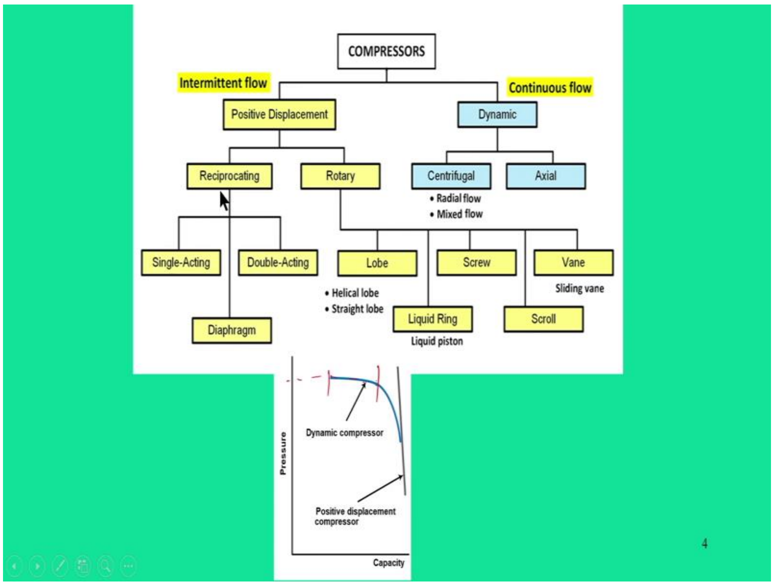

So, let me start with this compressor. Under the broad roof of compressors, there are many categories and we will be only focusing on reciprocating compressors. Now, if you look at the compressors, there are two broad categories, one is positive displacement type, other is dynamic type.

And basically, when you need a continuous flow we require a dynamic compressors. And here the entire philosophy is that the kinetic energy is imparted to the fluid, through rotation of impeller or these vanes and through this process, necessary kinetic energy is imparted to the blades. And through these dynamic actions the pressure ratio is obtained.

And under this dynamic nature we have centrifugal type, axial flow type. Under this heading we have radial flow, mixed flow category. So, these type of compressors are mainly find their applications in aircraft engines. And another way is looking at is the gas turbine engines.

But, the other category of compressors where we require very high-pressure ratio, that means we also do not require continuous flow type, we require for certain time you run the compressor, store it. And when your work is over, you can again store it. So, it is a kind of intermittent flow type. So, such a machine we call this as a positive displacement type.

Under this heading we have a reciprocating nature or we have rotary nature. Reciprocating or rotary here I mean, that reciprocating nature will have a piston and cylinder motions which is similar to IC engines, where there is a suction and there is a delivery or discharge. So, during the motion of the piston, the air gets compressed and other end the high pressure gas gets discharged.

And here also we can have a single acting and double acting. So, basically when we have reciprocating type of nature, so one is suction and other is discharge. So, in a single acting situation, there is one suction and one discharge, but in a double acting system when there is a suction in one side, there will be discharge in other side.

So, that is where we say it is a single acting and double acting type. Other nature is that there are diaphragm type. So, there is a diaphragm which gives the compressing nature of the fluid. So, it is also comes under these things.

And other domain of this positive displacement type is a rotary. Here the rotary I mean it is also an intermittent flow type, but other category is that, here these reciprocating nature is replaced with the rotary natures, and accordingly we have different versions, lobe types, screw type, vane type, liquid piston type, scroll type. So, this is not the part of our segment.

So, we will mainly say focus on a compressors, which is reciprocating nature and mostly single acting. And to some extent we will give some introduction how a double acting reciprocating compressor looks like.

The, another important aspect is that pressure and capacity. Pressure and capacity means basically, we require the fluid or charge or air that needs to be compressed. So, that means, its pressure needs to be high.

At the same time when we are going for high pressure, whether we can have a continuous flow type with very high flow rate or it can be a constant flow rate or it is a intermittent flow rate. So, that two parameters normally decides, what type of compressor is going to be used.

So, in a broad sense, if you try to plot the capacity versus pressure. In a positive displacement compressor type, mainly reciprocating nature type, we will find that it can cater a wide range of pressures, but at a given capacity. We cannot have a higher capacity continuously changing the flow capacity.

But, in a dynamic compression nature type what we can see is that with varying capacity we can have a fixed pressure. So, we can say, maybe for this range of capacity, we can operate at same pressure and with higher capacity the pressure will drop. So, this is mainly due to the dynamic nature or sometimes we call as a rotodynamic compressors.

So, this is the very ideal situations that is aircraft or gas turbine engines require. So, under that domain these dynamic compressors are widely used. So, basically, we are looking at a positive displacement compressor in this course, and we have mainly reciprocating compressors.

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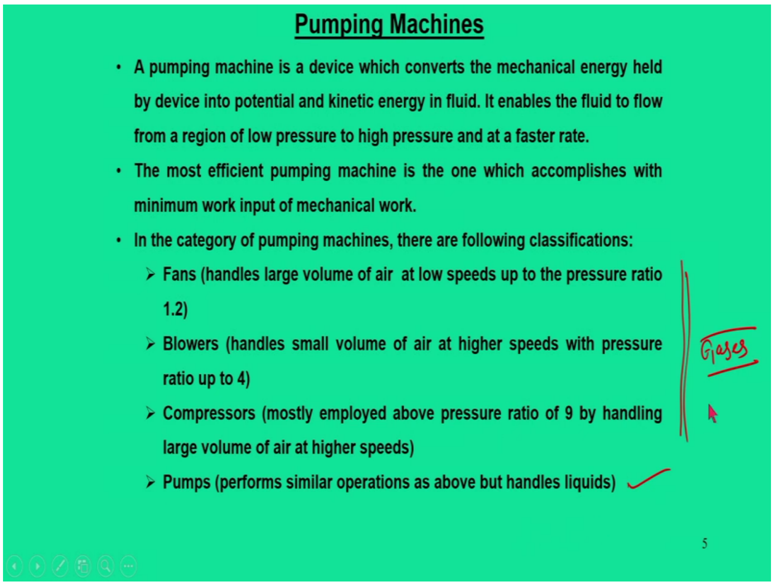

So, let me start this compressor with an introduction of what is a pumping machine. So, a pumping machine is a device which converts the mechanical energy held by the device into potential and kinetic energy of the fluid. Through this process it enables the fluid to flow from a region of low pressure to a high pressure and at a faster rate. The most efficient pumping machine is the one which accomplishes minimum work input for the mechanical work, for which it is intended.

And the category of pumping machines and we have fans, normally these fans they handle large volume of air at low speeds and up to pressure ratio of 1.2. We have blowers, they handle small volume flow of air, but at higher speed with a pressure ratio up to 4.

Then, next version is the compressors. So, they are mostly employed for the pressure ratio above 9 by handling large volume of air at higher speeds. So, this is how we have to deal with the compressors. So, normally fans or blower are the smaller version of the compressors. Since, they are intended for different pressure ratio and different flow rates, so names are given accordingly.

And these three are mainly for gases, but when we deal with liquids they also perform similar operations and we call this as pumps. So, these pumps you might have seen this in our turbo machines fluid mechanics course, the pumps we have centrifugal pumps, we have axial flow pump, we have reciprocating pumps for the applications. But, our main target will be on compressors.

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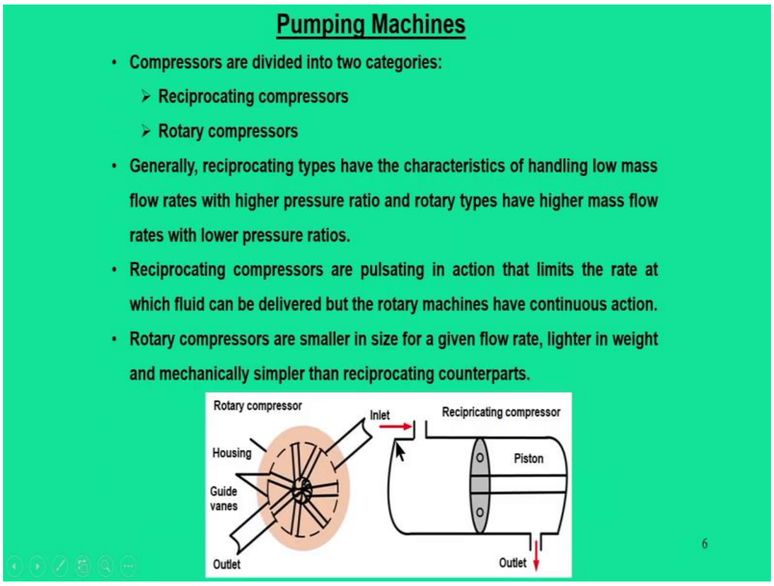

There are two broad categories of pumping machine, one is reciprocating type, other is rotary type. So, if you can broadly see this figure that there is an inlet, there is an outlet. So, what we can see is that during the suction stroke in a reciprocating compressors, the air gets into the cylinder, and it gets compressed and finally, there is a outlet in which gas is discharged.

And similar thing which is attend through the rotary nature of another version of this particular compressors where we have guide vanes. So, basically rotary means there is a motor or shaft that rotates. And there are guide vanes, and these guide vanes allows the control inlet of air or gas, and it goes out in another outlet. So, basically, both are doing the same version; one version is achieved through the reciprocating nature of the piston, other version is achieved rotation of the shaft.

The reciprocating compressor types have characteristics, handling a low mass flow rates, but with a higher-pressure ratio, and rotary types have higher mass flow rate, but at lower pressure ratio. Reciprocating compressors are pulsating in action that limits the rate at which it can be delivered, but rotary motions have continuous action. Rotary compressors are smaller in size for a given flow rate, lighter in weight and mechanically simple than the reciprocating counterparts.

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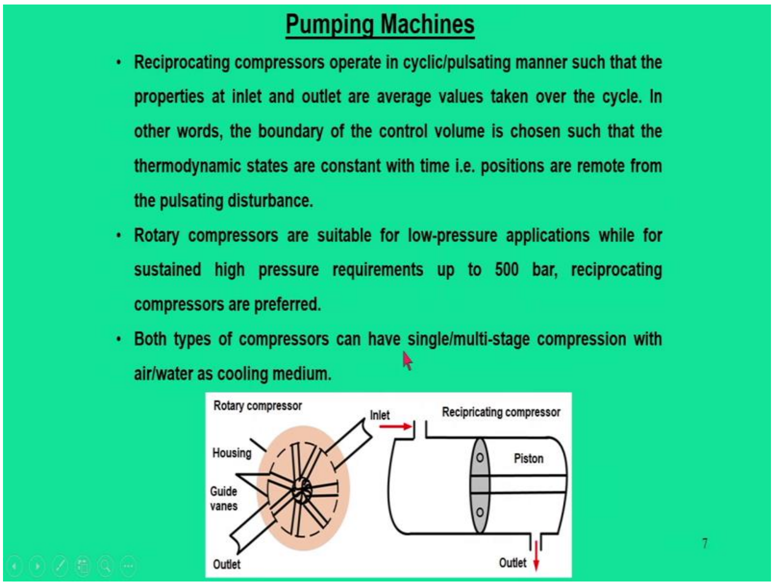

The reciprocating compressors operate cyclic or pulsating manner such that properties at the inlet and outlet at the average values taken over the cycle. And the boundary of the control volume is chosen such that the thermodynamic states are constant; that means, positions are remote from the pulsating disturbance.

So, we will discuss more how we are going to deal with the analysis. But, in other hand, the rotary compressors find suitable in low pressure applications while for high pressure requirement up to 500 bar or reciprocating compressor are preferred. And irrespective of what type of compressors we have, the normally the compressor deal with single-stage and multi-stage compression with the air and water as the cooling medium.

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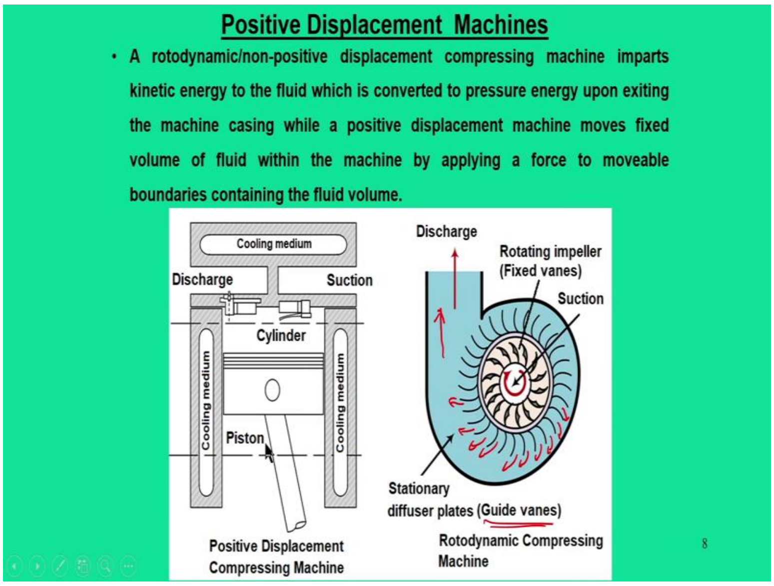

The, another way of classifying this pumping machine is a positive displacement and rotodynamics displacements. So, if you can the see this kind of a graphical or construction picture of a positive machines and a rotodynamic machines. What we can see? In a positive displacement machines, we have a piston cylinder, we have suction and we have discharge. So, we will discuss more details on this.

So, what happens? The reciprocating motion of the pistons allows the air to be get compressed, and finally, we get the desired pressure at the discharge end. But, on the other hand, the rotodynamic type machines, we have rotating impeller which has fixed blades and there is a suction when the fluid gets sucked in, the rotating action of this impeller fixed vanes imparts kinetic energy to the fluid.

And when this kinetic energy again passes through the stationary diffuser plates, which are fixed at the other periphery outside this impeller. So, as a result, discharge or flow that comes out through this diffuser nature of this passage, and these are what you call as guide vanes. And finally, the overall discharge or flow rate that goes out.

So, this rotodynamic machine is a non-positive displacement machines. And more details on this we will find in aircraft propulsion topics, or similar topics we can find centrifugal pump suction, where water is used which which we have studied in the fluid mechanics topics.

But, in our applied thermodynamics case we will only deal with the compressor, since we are dealing with air. And we will mainly focus on the positive displacement type machines that is reciprocating compressors.

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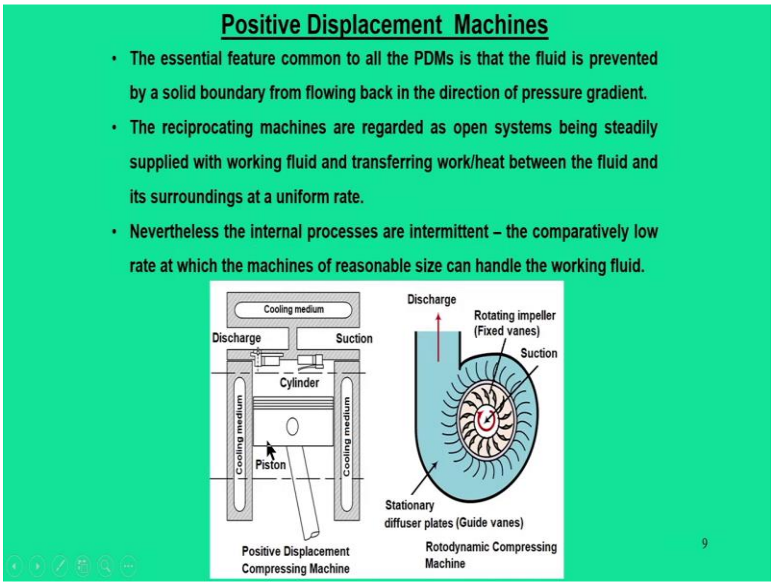

The other important essential features of positive displacement machine is that, fluid is prevented by the solid boundary from flowing back in the direction of pressure gradient. The reciprocating machines are regarded as the open systems being steadily supplied with working fluid and transferring work or heat between the fluid and its surroundings at uniform rate.

We will deal this thermodynamic modelling for this particular segment. Nevertheless, the internal process are intermittent, the comparatively low rate at which the machines have reasonable size can handle the working fluid.

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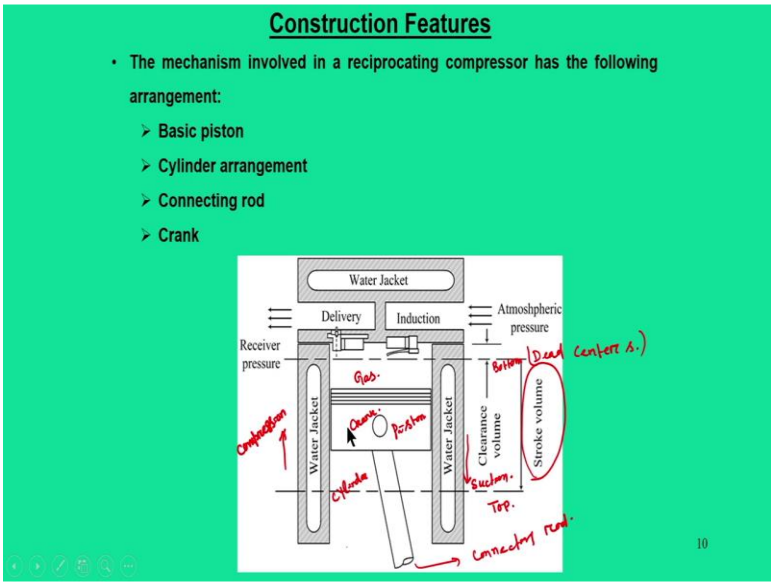

Now, let me come to the construction features of a reciprocating compressors. So, looking at the figure what we have seen is that we have a cylinder, which is housing a piston. So, we can call this as a piston, and we have cylinder and this piston is connected to a connecting rod, separately.

Now, what happens? The atmospheric air enters through this induction systems or induction mechanism and there is a valve. During the suction stroke; that means, the piston moves outward, that is suction. So during the suction stroke, the intake valve opens, so the induction of air into the cylinder starts and the cylinder is filled with the gas.

Now, the piston has two extreme limits, one is the dead center and in IC engine terminology, this we called as a TDC or BDC, but here we will not use the word TDC and BDC. But, we will put these two limits in which the piston moves and that limit we call this as a stroke volume. And this is the bottom limit, and this is the top limit. And the entire gas which gets sucked into this cylinder, it can go up to the piston position when it is in the top locations.

Now, when the compression stroke starts, the piston moves backward. So, we call this as a compression stroke. And during this compression stroke the entire gas squeezed in a very small volume and that we call as clearance volume. That means, piston can go up to the upper limit that is bottom limit, and entire gas that gets squeezed in a very small volume we call this as a clearance volume. Once the compression is over, then these delivery valve can open, and delivery will start.

Now, when this compression is done, then the temperature also increases. So, it is likely that the components gets heated. So, to get rid of this heating process, we have water jackets, all around the piston as well as around the delivery and suction locations. So, as a results, we can provide necessary cooling to protect the components.

So, this is how the basic operation of a reciprocating compressors that involves the basic pistons, cylinder arrangement, connecting rod and crank. This crank is here in which the piston is connect connected to the connecting rod.

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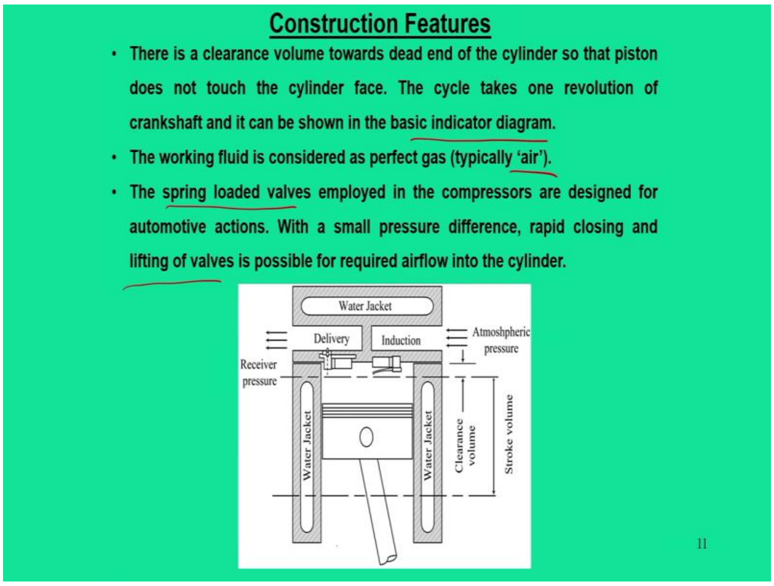

So, there is a clearance volume which I have already mentioned that towards the dead centre of the cylinder, so that piston does not touch the cylinder face. That is the first requirement. This cycle takes one revolution of the crankshaft and it can be shown as a indicator diagram. The word indicator diagram in thermodynamic sense we call this as a pressure volume diagram.

And here we will talk about the working fluid which is a perfect gas, and mostly we will talk about air. And in our day-to-day life reciprocating air compressors are very common. And there are also spring loaded valves. These valves are employed in the compressors that are designed for automotive action, which means that with a small pressure difference rapid closing and lifting of the valve is possible for required air flow rate into the cylinders.

So, ideally, speaking you require a automotive actions that the valve should open and close. So, this is a automotive actions, and this automotive action has to be performed at synchronized manner. And there is a issue called as a lifting of valves. So, valve gets lifted again that gets closed. So, this continuous process is normally controlled through cam mechanisms, so which is typically similar to IC engine components.

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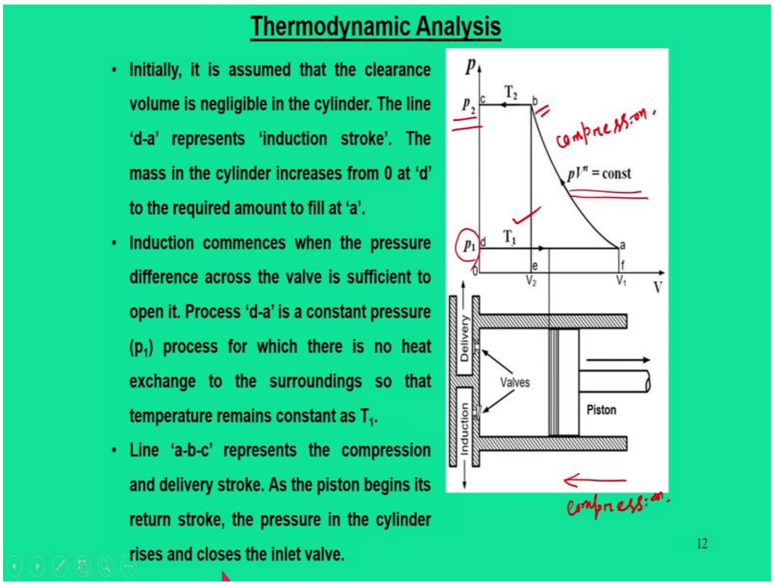

Now, let us see the thermodynamic nature or analysis for this reciprocating action of a gas in a compressors. And this schematic representations shows that the location of piston in any arbitrary positions.

And we have two pressure ratios; that means, one side we need air to get sucked in, so which is a the suction pressure or typically where this machine is installed we call this as a atmospheric pressure, and p_2 is the pressure that the delivery side we require. So, it is a delivery pressures.

And this compression process is given a thermodynamic equation $pv^n = C$. So, it is a polytrophic equation, and for different values of n or exponent, we can define these thermodynamic processes, whether it is a isothermal process or a isentropic process or in a simple compression process, we write it as $pv^n = C$.

And we will discuss in the latter part, what is the importance of n, why we cannot have n is equal to gamma or n is equal to 1, all this. Why we cannot have isothermal or adiabatic or any isentropic processes? But, what value of n is best suited for a compressing action?

So, initially it is assumed that the clearance volume is negligible for the cylinder. So, in this particular figure, we have assumed that there is no clearance volume. So, as if that piston exactly reaches this dead end of the cylinder and again after the compressor and again comes back from that.

So if you look at this particular diagram in a p-V plot, the line d-a represents the induction stroke that is the mass in the cylinder increases from 0 to d. So, from 0 to d, the mass in the cylinder increases to the required amount to fill at ‘a’. That means, at ‘a’ entire mass which is supposed to be compressed gets inducted till the point ‘a’.

So, that means, at point ‘a’ the induction commences; that means, we require only this many mass or charge that needs to be compressed. So, once the induction commences, the pressure difference across the valve is sufficient to open it. So, the process d-a is a constant pressure for which there is no heat exchange to the surrounding and temperature remains constant T_1 at that situation.

So, now we will see that line a-b-c. So, it represents the compression and delivery stroke. So, as the piston begins to return stroke, the pressure in the cylinder rises. That means, once the induction is over from point ‘a’, the piston moves back, so that we call as compression.

And how long it goes? It goes up to point b. So, this compression is given by this equation. So, as the piston begins to return stroke, pressure in the cylinder rises and closes the inlet valve.

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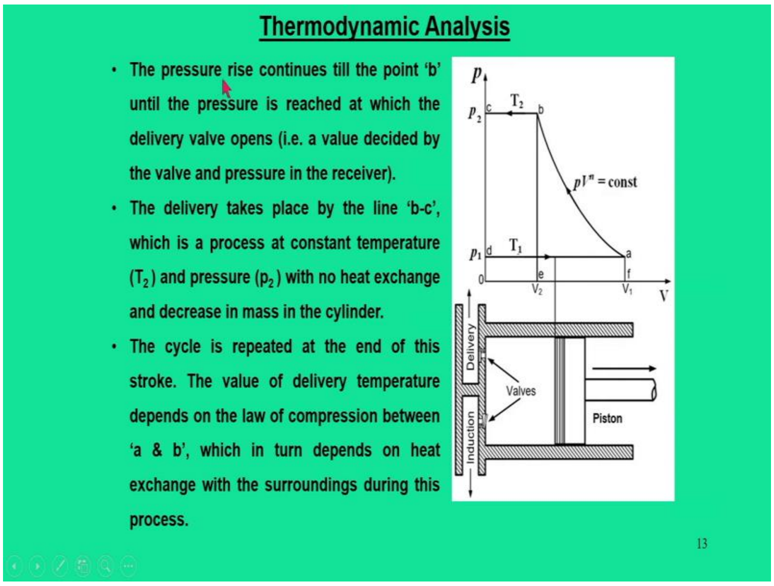

How long pressure keeps on rising? It goes rising till the point b until the pressure is reached at which the delivery valve opens. That means, till we reach this desired pressure p_2, the delivery valve opens, and its value is decided by the value and pressure in the receiver. So, delivery means it goes to another container or receiver where the needs to be stored.

The delivery takes place in the line b-c. So, at this temperature the delivery stroke starts from b to c. So, the cycle is repeated at this end of the stroke. The value of delivery temperature depends on the law of compression between state a and b, which in turn depends on the heat exchange with the surrounding during this process.

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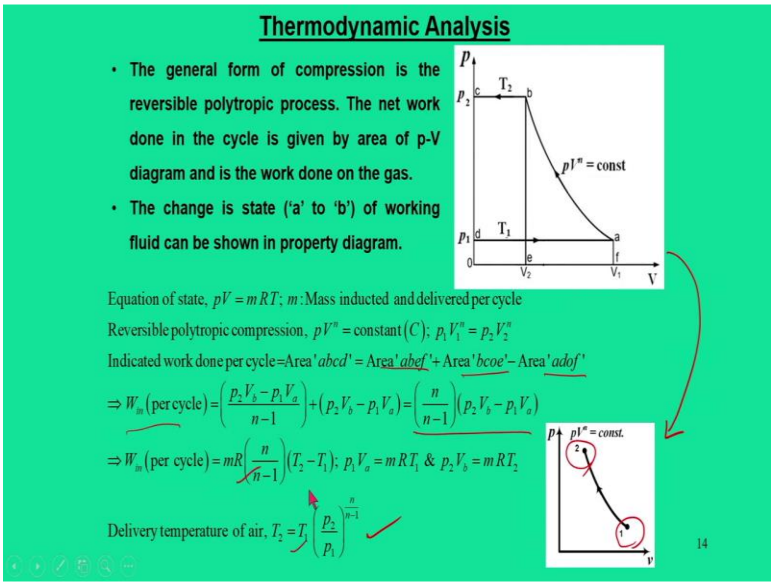

Now, from these we can frame a general thermodynamic equations how much mass gets inducted, and how what is this thermodynamic processes and how much work is required to compress certain slog of mass.

So, we will now work on this particular p-V diagram, because the pressure volume diagram is very basics. And ultimately, after explaining actual process from a to b and c, but a simplified version of this, is writing a simple equation in p-V diagrams where the initial state is 1 and final state is 2. And through this initial and final state, this process happens a to b.

So, in the end, so if you can summarize this particular entire events, we can we summarize in just one diagram where the thermodynamic state of a given gas gets changed from the state 1 to state 2 by following the law of compressions $pv^n = C$.

Now, let us recall our equation of state that is $pV = mRT$, which is mass inducted and delivered per cycle. So, you know m. So, for a reversible polytropic compression equation we say $pV^n = \text{constant}$, so that we can write $p_1 V_1^n = p_2 V_2^n$.

Now, from this p-V diagram what we can see is that work done per cycle it is nothing but area abcd. And this area is nothing but area abef + area bcoe - area adof. Now, most of the diagram they are rectangle and other areas we can find out from this thermodynamic equations $pV^n = \text{constant}$. So, indicated work done per cycle is nothing but the work input per cycle.

So, ultimately, when you simplify this equations, we will write that the work done per cycle is $\left(\frac{p_2 V_b - p_1 V_a}{n-1}\right) + \left(p_2 V_b - p_1 V_a\right) = \left(\frac{n}{n-1}\right)\left(p_2 V_b - p_1 V_a\right)$. So, this is nothing but $p_1 V_a = mRT_1$ & $p_2 V_b = mRT_2$. So, roughly speaking that we can simply say that $p_1 V_1 = mRT_1$ & $p_2 V_2 = mRT_2$.

And finally, what we get is work input per cycle is only a function of the temperatures at which they are operating. And here the pressure is now immaterial here, but this temperature is also a function of pressure ratio. So, to find T_2 we also require p of the equations, $T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$ and from this also we can get a delivery temperatures. So, these two equations are now backbone or very basics for the reciprocating compressors.

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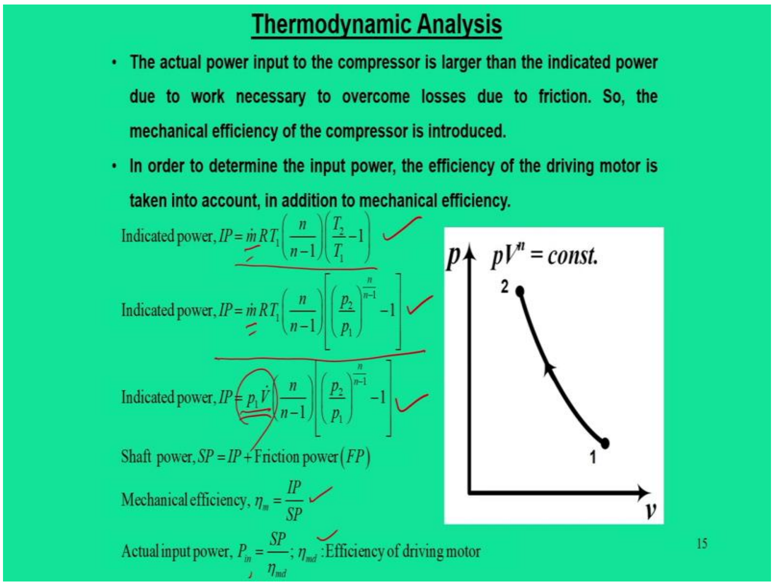

Now, moving further, now come up with expressions that indicated power which is $\dot{m}RT_1\left(\frac{n}{n-1}\right)\left(\frac{T_2}{T_1}-1\right)$. And putting this $\frac{T_2}{T_1}$ as a function of $\frac{p_2}{p_1}$, because many a times pressures are measurable quantity. So, the working equation for a compressor now becomes is indicated power $IP = \dot{m}RT_1\left(\frac{n}{n-1}\right)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}-1\right]$.

Many a times we do not know mass flow rate, and mainly when you have incompressible nature, volume flow rate is a typical way of expressing this mass of the gas. So, we can represent in terms of volume flow rate.

So, volume $\dot{m}RT_1$ that can be replaced with initial pressure into this volume flow rate. $IP = p_1\dot{V}\left(\frac{n}{n-1}\right)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}-1\right]$. So, this is how we indicated power has basically three version in terms of temperature ratio, in terms of pressure ratio, and both are in the form of mass flow rate. Another version of equation is that in pressure ratio and in the form of volume flow rate. So, these basic equations are very vital for a study of compressor.

Now, once we know the indicated power, there is also possibilities that the actual power input to the compressor is larger than that of indicated power. To just to overcome the losses due to friction, so we introduce a term what we call as a mechanical efficiency of the compressors. And that is nothing but the indicated power divided by the shaft power.

And how this shaft power is calculated? The shaft power is calculated when we add indicated power to this friction power, we get the shaft power. That is what the mechanical efficiency is defined $\eta_m = \frac{IP}{SP}$.

Now, when you have shaft power then how much power we are going to apply for running the compressors that is given by efficiency of driving motor. So, actual input power which is required is the shaft power divided by efficiency of driving motor. So, shaft power already computed, so we can find out the actual power input. $P_{in} = \frac{SP}{\eta_{md}};\ \eta_{md}: \text{Efficiency of driving motor}$

So, through this process from the indicated power to this power input, there are two efficiency, one is mechanical efficiency, other is the efficiency of the driving motor. And in fact, this is a continuous process and these efficiencies are also very vital to know the actual power that is required to handle certain mass flow rate of air or volume flow rate of air for operating a given pressure ratio.

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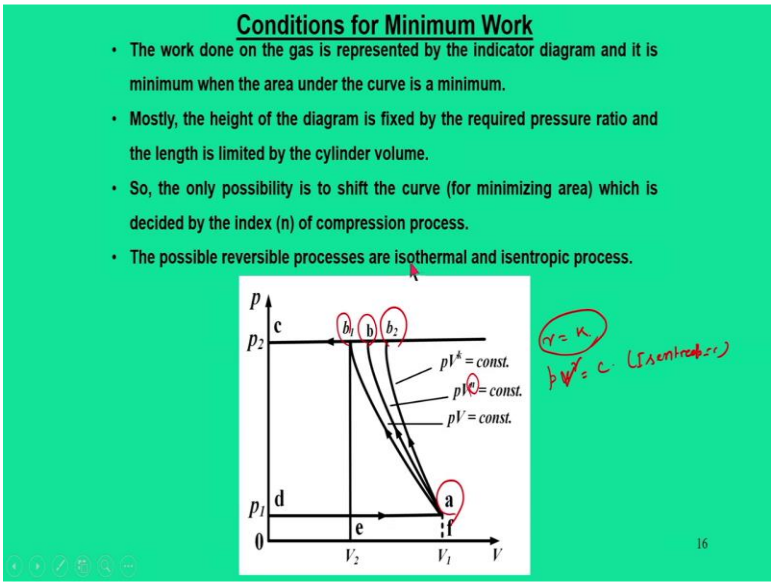

Another important segment of this compression work is that conditions for minimum work. So, an ideal compressor is the one which consumes minimum work for a given pressure ratio. So, the work done on the gas is represented by the indicator diagram, and it is the minimum one, under the curve is minimum.

So, mostly for a compressor situations, the height of the diagram is fixed by the required pressure ratio. Height means if you look at this p-V diagram, the height of this diagram is fixed by the pressure ratio in which we are handling. So, under these two pressure ratio, we need to fit a compression curve, now which is the best. Then, length is limited by the cylinder volume. So, if you have a given size; that means, we need to have fixed pressure and we have fixed size of the cylinder. So, that is limited.

Now, under these things we have to fit a curve which is supposed to have a minimum area under it. So, this is possible only when if you can play with the index of compression that is n. So, n is typically unknown quantities. Until this point of time if you look at the idealic nature of the plot, so we have three situations; one is state 'a' where the compression has to start, and we have three locations, one is b, we have a b_1 and b_2, so three locations, and these three locations are extreme locations.

So, we can have a process like a-b, we can have a process a-b_1 or we can have a process a-b_2. And all these processes is done for a given size of the cylinder or shaft volume of the cylinder and for required pressure range p_2 and p_1.

And what are these three curve indicates? Now, in one situation, we assume that n is equal to 1, so it is a $pV = \text{constant}$ which is nothing but an isothermal process. In other extremes, we have $pV^k = \text{constant}$, where k = γ and if you say $pV^\gamma = \text{constant}$ then it is a isentropic process.

Now, when doing this nature of the curve we can see that only if the process is isothermal, the area under that curve will be minimum. It is a natural nature that when there is a compression the temperature is going to increase, but when a temperature is going to increase and side by side the process need to be isothermal, so it is a hypothetical case.

So, but the thermodynamic nature for the process that tells us that we need to have an isothermal process if the area under that curve is a minimum. So, there are two extremes isothermal and isentropic processes.

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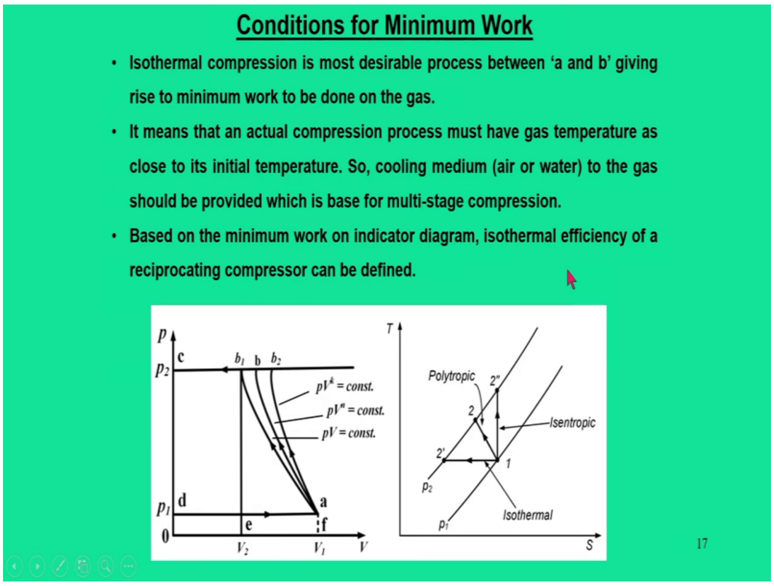

Now, what we can see is that if you try to recall this diagram in a TS plot and there are two pressure ratios p_1, p_2, and isothermal process will take you in a straight line which is parallel to entropy axis.

And another straight line would be 1-2`, which is just a vertical which is parallel to the temperature axis and this is an isentropic process. And somewhere another process will be 1-2 which is in between and that is the region we have put n here. So, we cannot have isothermal process, even we cannot have isentropic process. Isentropic process means area will be the highest.

So, isothermal compression is the most desirable process between a and b giving rise to minimum work done on the gas. So, it means that actual compression process must have gas temperature as close to the initial temperatures. So, that means, after compressor you have to keep on continuously cooling.

That is what I told that, when the compression is normally done side by side cooling is provided, so that to the best possible extent we do not rise the temperature after during compression. So, based on the minimum work in the indicator diagram, we can now fix the isothermal efficiency.

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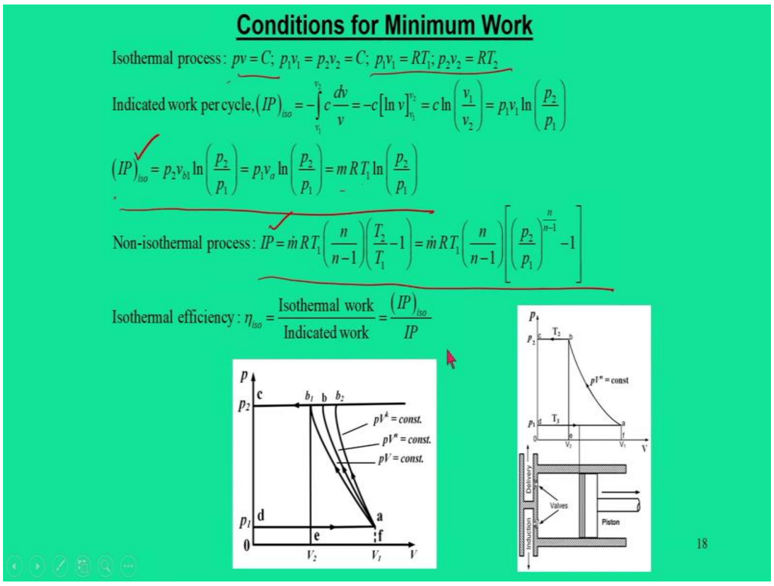

So, this is what we have summarized is that we have now two works, which is indicated work, one is a non-isothermal process which we have already derived these expressions.

$$IP = \dot{m}RT_1\left(\frac{n}{n-1}\right)\left(\frac{T_2}{T_1}-1\right) = \dot{m}RT_1\left(\frac{n}{n-1}\right)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}-1\right]$$

Other way is that we can find out the same expressions that is indicated for power for an isothermal process. And for an isothermal process we can write this $pv = C;\ p_1v_1 = p_2v_2 = C;$. We have $p_1v_1 = RT_1; p_2v_2 = RT_2$.

So, accordingly, based on these equations if you can start from the basic principle, you can find out indicated work per cycle, we can write in the form that $mRT_1 \ln\left(\frac{p_2}{p_1}\right)$. So, this is how we get isothermal work.

So, as isothermal work is the work input for the compression which is minimum, and indicated work is actual work. So, it is a ratio between these two will give you the isothermal efficiency.

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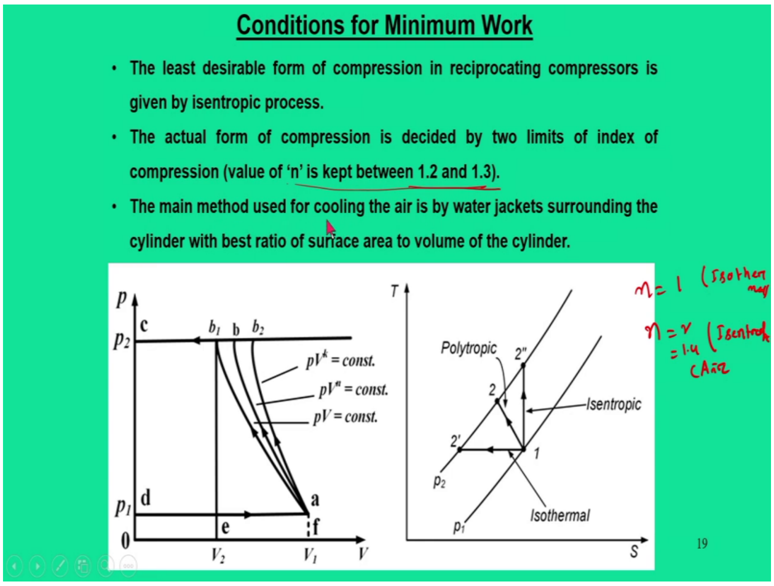

Another important point that I need to emphasize that what is the value of n typically maintained. So, as I mentioned the least desirable form of compressions in a reciprocating compressor is given by an isentropic process.

So, till this point of time always we see that isentropic process is a reversible one, it is a unique way to define the reference state of any given process. But, here this is completely avoided when you deal with the reciprocating compressors. So, isentropic process is the least desirable form of compression process, and in particular when we are looking at the reciprocating compressors.

So, the actual form of compression is decided by two limits of index of compressions, and that is n is equal to 1 and n is equal to γ. Now, when you are dealing with air compressors, so you have to keep normally a intermediate number n, which is kept in the range of 1.2 and 1.3. And another way of conclusion that will get draw is that if you want to minimize the work input, then we must provide continuous cooling. So, the main method of the cooling of air is by water jackets surrounding the cylinder with best ratio of surface area to volume of the cylinder.

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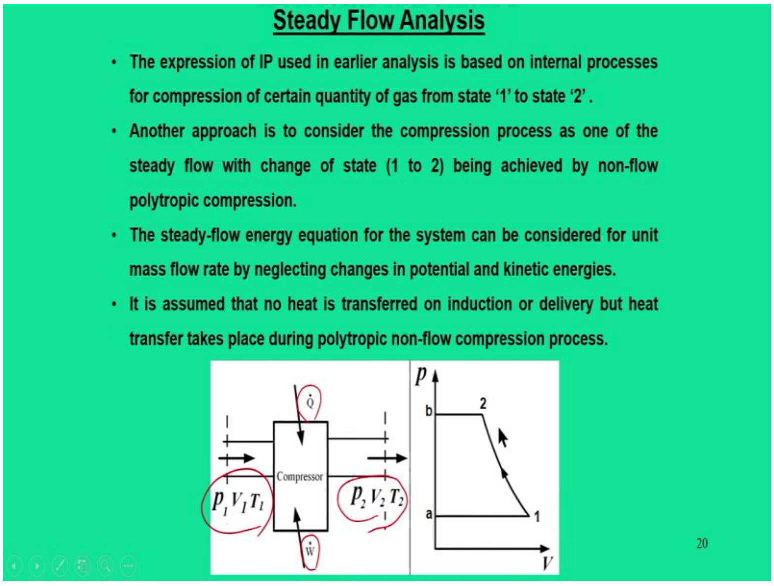

Now, the last segment of our discussion in our course is that a steady flow analysis. So, in one way that we have discussed about what is the power requirement for the compressors, and we say that when you deal with the compressor, that was a situation where we dealt with a non-steady system, it is a closed system type.

Now, we can do another modelling in which we can work on a steady flow analysis. So, what does this mean? That, if you can think that a compressor is a device in which there is some slog of gas at pressure p_1, volume V_1, and T_1, that enters, and it goes out at different states p_2, V_2, T_2, so obviously, p_2 is higher than p_1 and temperature is also higher than T_1.

And this compression process goes from 1 to 2, when it goes from state a to b; now, what happens? In this process, if you say it is a steady flow it can undergo heat interaction and one work interactions. So, this is your problem how you are going to deal with.

So, in a steady flow analysis, we think the compression process is one of the steady flow with change of state from 1 to 2, and which is achieved by a non-flow polytropic compression. The steady flow energy equations for the systems can be considered for the unit mass flow rate by neglecting changes in the potential and kinetic energies.

Now, also it is assumed that no heat is transferred on the introduction or delivery, but heat transfer can takes place during the polytropic or non-flow compression process. So, that means, this heat is getting transferred only during the process 1 to 2. So, none other way that it can go in, only during this process 1 to 2.

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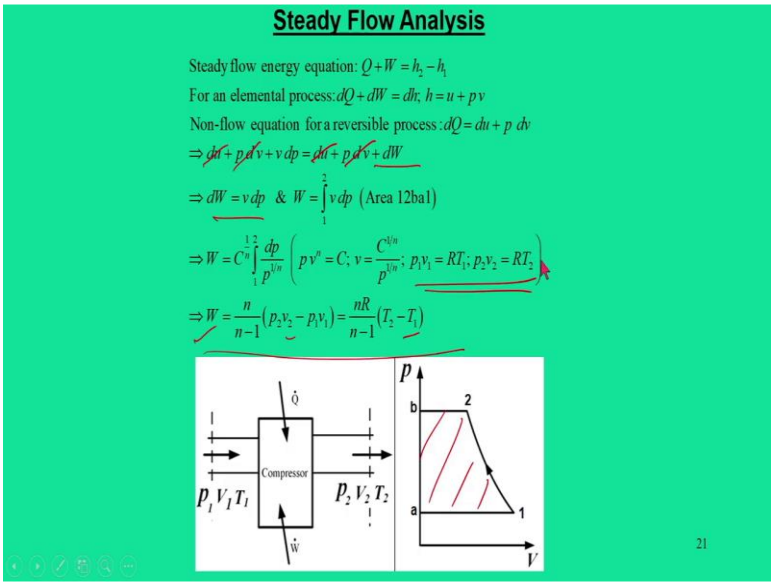

So, if you can recall our steady flow energy equation again from the first law for open system by neglecting kinetic energy and potential energy, we can write $Q+W=h_2-h_1$ and here for an element process $dQ+dW=dh$.

Now, if you recall that what is h, $h=u+pv$ that is enthalpy is equal to internal energy plus flow work. And also from this we can write now $dQ=du+p\ dv$.

Now, by putting this equations, ultimately we can now rewrite the fact that we can equate $du+p\,d\,v+v\,dp=du+p\,d\,v+dW$ and this pdv gets cancelled and du also gets cancelled, so we can write $dW=v\,dp$. And from this we can integrate $W=\int_1^2 v\,dp$ (Area 12ba1). So, this is the area under which we are going to calculate this work.

And from this we can now write what is v, $p v^n = C$. So, $v = \frac{C^{1/n}}{p^{1/n}}$, and from this we can integrate this equation $W = C^{\frac{1}{n}} \int_1^2 \frac{dp}{p^{1/n}}$. And finally, we can land off the same expressions that is $W = \frac{n}{n-1}\left(p_2 v_2 - p_1 v_1\right) = \frac{nR}{n-1}\left(T_2 - T_1\right)$.

But, the entire philosophy is that at the end of our analysis, we again come back to the same virtual expressions that is W, as a function of pressures as well as temperatures. And we also get the equations that is work required for the compression.

And the more or less the equation remains same, but our approach was different. So, there in the first case it was a closed system approach, and in the second case we have a steady flow systems. But, at the end of the day, what the main requirement is that we have to find the work input for the compressors.

And this work input is normally represented or we call in this compressor term as the indicated power and this is calculated per cycle, if there are n number of cycles accordingly volume will change. So, this is all about the entire contents for this lecture today.

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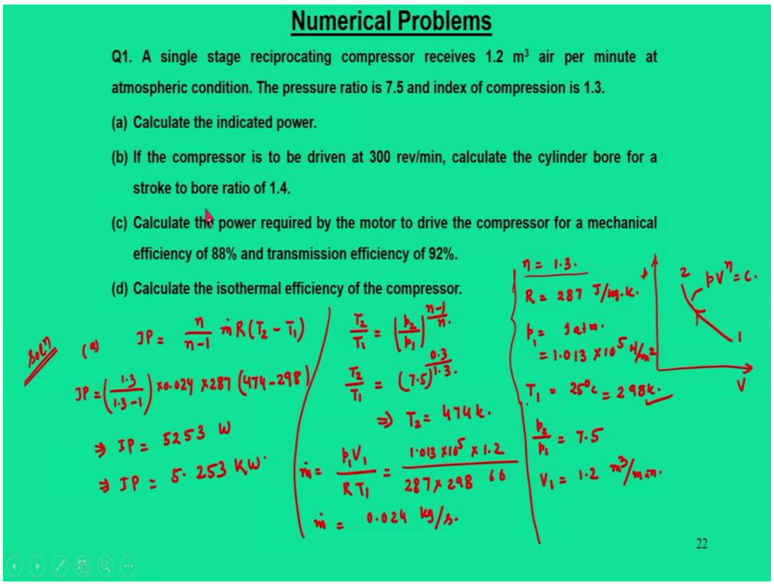

Now, we will try to solve a numerical problems based on the discussions what we have learned today. So, the question that was given that we have a single stage reciprocating compressors. It receives 1.2 m^3 of air per minute at atmospheric conditions. That means, atmospheric air enters to the compressors at a flow rate of 1.2 m^3.

And the pressure ratio is 7.5; that means, the pressure is increased 7.5 than the atmospheric pressures. And for which the index of compression is 1.3; that means, here we have given n is equal to 1.3.

So, you have to calculate the following indicated power. And if the compressor is driven by 300 revolution per minute, we have to find the size of the cylinder bore. Third thing we have to calculate the power required for the motor and fourth is isothermal efficiency. So, let us try to solve this problem.

So, when you deal this compression problem the first thing you have to show what is the thermodynamic processes that is involved here. So, we first we have to draw the p-V diagram, and the process we have to represent as 1 to 2, and this is $pV^n = \text{constant}$.

So, here given n = 1.3 and here it is air, so for air R is equal to 287 j/kg-K. And remember here n is not equal to γ. Even though we say air, but n you are taking 1.3. Then, we have pressure which is 1 atmosphere. This 1 atmosphere is nothing but $1.013*10^5$ N/m^2.

And we have temperatures, temperature T_1, we can assume to be 25°C that is 298K. And we also have $\frac{p_2}{p_1}$ ratio as 7.5 and V_1 which is given as 1.2 m^3/min. So, now we have to calculate.

So, first question that is we have to find the indicated power. So, if you recall this indicated power equation $IP = \dot{m}R\left(\frac{n}{n-1}\right)(T_2 - T_1)$. So, first thing we have to find $\frac{T_2}{T_1}$.

Say $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$. So, we can get T_2 as 474K. Then, we have to find out a mass flow rate. So, for mass flow rate, we can write $\dot{m} = \frac{p_1 V_1}{RT_1}$. So, we can find m = 0.024 kg/s.

Now, we can calculate now IP is equal to 5253 w or 5.253 kw. So, this is the first part.

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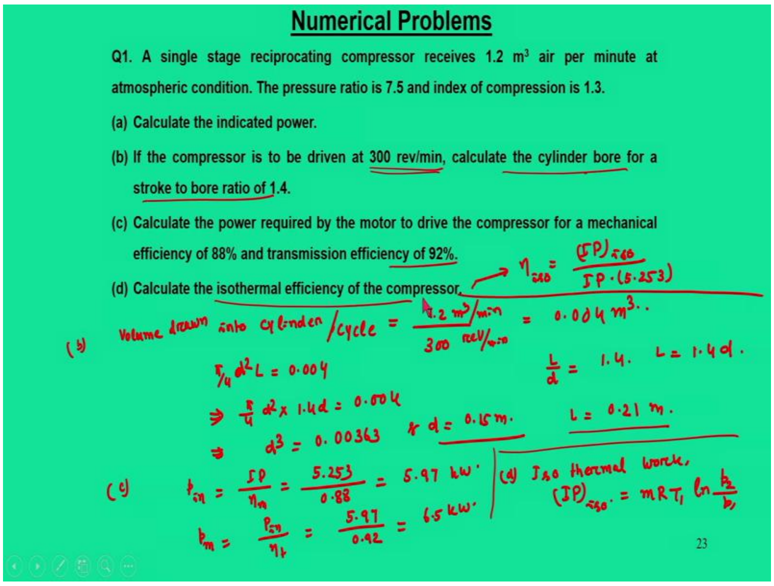

If the compressor is driven at 300 revolution per minute, we have to find out what is volume drawn into the cylinder per cycle. You have flow rate is 1.2 m^3 and 300 revolution per minute, so this will give you 0.004 m^3.

And we are given with stroke to bore ratio that means, L/D = 1.4. So, you can write the volume of the cylinder $\frac{\pi}{4}d^2L = 0.004$. And from this, $\frac{\pi}{4}d^2 \times 1.4d = 0.004$. So, this will give you d = 0.15m. So, L will be 0.21m.

Third question is power driven by the motor to drive the compressor. So, that is nothing but $p_{in} = \frac{IP}{\eta_m}$. So, this is 5.253 / 0.88 and this number is 5.97 kW.

And what is power required to drive the motor? $p_m = \frac{p_{in}}{\eta_T} = \frac{5.97}{0.92} = 6.5\text{kW}$. And last is isothermal efficiency I am leaving it to you. We have to calculate the isothermal work. So, that is for minimum work.

So, we can have indicated power isothermal $(IP)_{iso} = m R T_1 \ln\left(\frac{p_2}{p_1}\right)$. So, $\eta_{iso} = \frac{(IP)_{iso}}{IP}$ and this IP is already 5.253. So, we can find the isothermal efficiency by taking that ratio.

So, with this, I come to end of this today's lecture.

Thank you for your attention.