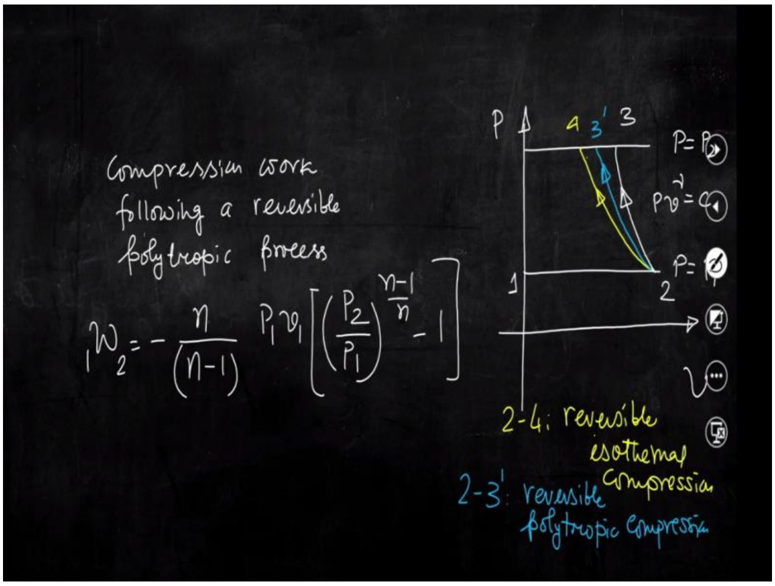
Thermal Engineering Basic and Applied
Prof: Pranab K Mondal
Department of Mechanical Engineering
Indian Institute of Technology – Guwahati

Lecture - 64
Compressor Efficiency and Multistage Compression with Intercooling

Very good afternoon I welcome you all to the session of Thermal Engineering Basic and Applied and today we shall discuss about the compressor efficiency and then we shall start our discussion on another aspect of the gas turbine units that is the multistage compression with intercooling. So, in the last class we have established the mathematical expression of work done needed to be supplied to run the compressor following several processes and those processes are reversible adiabatic compression, reversible isothermal compression and a more generic process that is reversible poly tropic compression.

(Refer Slide Time: 01:22)

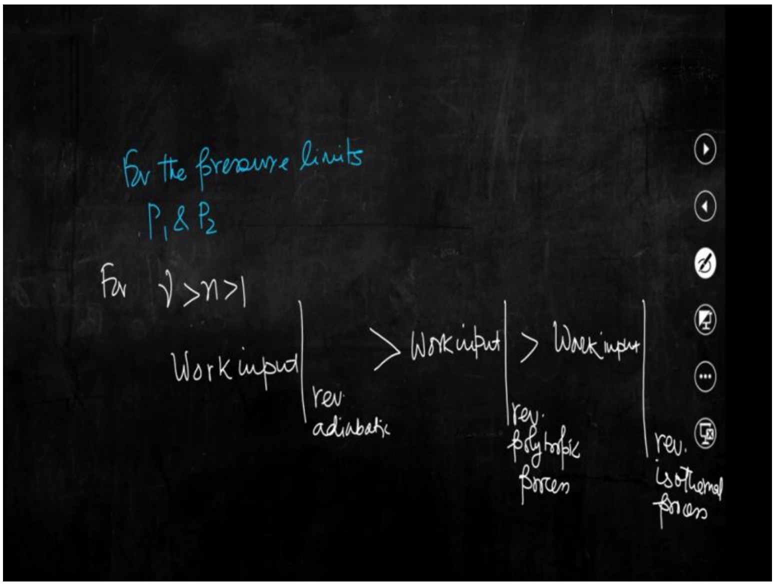


So, if we write here that compression work following a reversible poly tropic process then this expression should be $_1^{}w_2 = -\frac{n}{n-1} p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$. So, this is the expression of the work done needed to be supplied to the compressor while the working fluid will be compressed following a reversible polytropic process. This negative sign as I said you that this is basically you know an indication of work input to the system following the notation that we could write in the last class that work added to the system is negative, work extracted from the system is positive.

Now today we shall you know discuss graphically you know that if we try to map the compression processes in P-v plane from a graphical representation of those processes we also can estimate qualitatively about the compression work, rather amount of compression work that would be needed to be supplied. So, if I write here, so this is P-v plane and if we assume that the compression process between two pressure $p = p_1$ and $p = p_2$.

So, these are the pressure limits and if we now consider this is point 1, this is point 2 and then this is 3, so basically you know that from pressure P2 to P3 we need to raise the pressure of the working fluid and this is $pv^{\gamma} = C$. Now, if we consider the compression process is reversible isothermal. So, this is 4; we can write that 2 to 4 is reversible isothermal compression and then reversible poly tropic process is in between these two and so this is $3'$. So, $2 - 3'$ so this is reversible poly tropic compression.

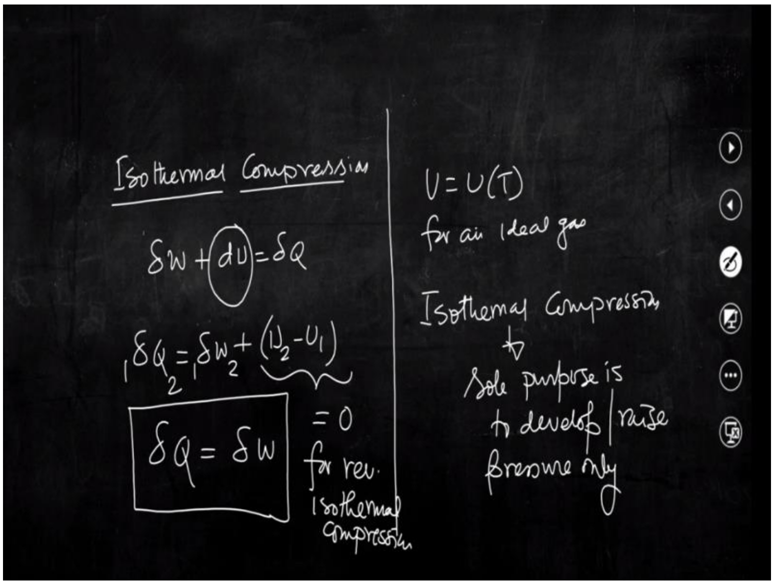
(Refer Slide Time: 06:30)



So, if we write here for the pressure limits that is $p_1$and p_2 then for $\gamma > n > 1$ you know work done or work input to the compressor following reversible adiabatic process is greater than work input following reversible poly tropic process which is greater than following reversible isothermal process. So, this is basically what we can see without going into the mathematical calculation. Just from the graphical representation of the process lines in Pv plane. We can assess certainly qualitatively about the work that we need to supply to the compressor for the compression process. Also from here we can see that work to be supplied to the compressor following a reversible isothermal process is certainly less as compared to the work needed for other two processes that means if the process is reversible adiabatic process compression then amount of work to be supplied to the compressors is maximum. So, if the work input to the compressor is significantly small than the work required for the compression following reversible adiabatic process.

Then it would be more economical performance wise to have a reversible isothermal compression because we had seen that a significant part of the turbine work output is consumed by the compressor for the compression process. Now for the reversible isothermal compression as I discussed in the last class it is very difficult to achieve and it is not of that much use in practice and in a reversible isothermal compression work done on the gas during the process is transformed into an increase in the internal energy.

(Refer Slide Time: 10:09)



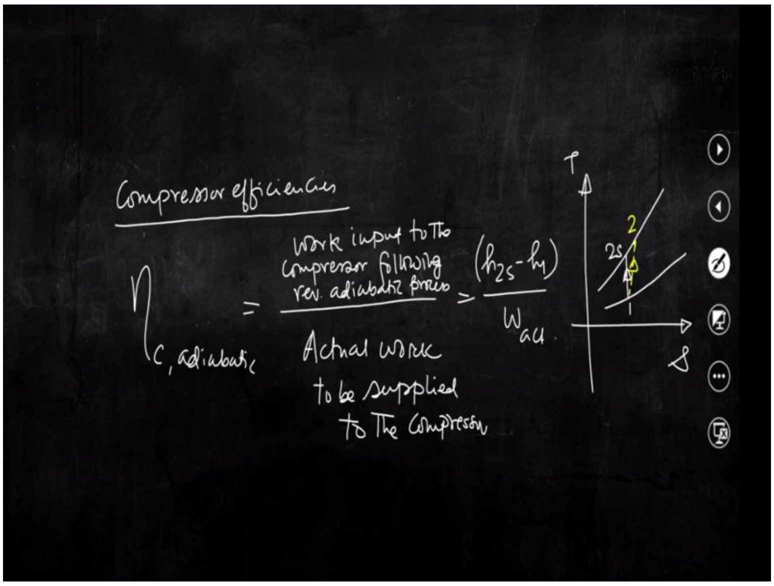
So, if we write the isothermal compression then we can write $\delta w + du = \delta Q$. Now for the reversible compression process following isothermal compression, we are supplying certain amount of energy in the form of work and that work done on the gas during the process will be transformed into an increase in the internal energy that means $\frac{1}{2}\delta Q = \frac{1}{2}\delta w + (U_2 - U_1)$. Now we know that for an ideal gas, internal energy and enthalpy is function of temperature only. In fact internal energy and enthalpy of an ideal gas is not function of volume and pressure as well. So, it is dependence on temperature only.

The process is isothermal compression so we are not allowing the temperature to be increased during the compression process of the working fluid. So, U equal to function of temperature only for an ideal gas and we can see that the temperature is remaining constant during the compression process. Hence, we can write this $\delta w = \delta Q$ as $U_2 - U_1 = 0$ for reversible isothermal compression.

So, what we can understand that the amount of energy that is supplied to the compressor in the form of work for which rise in temperature will be there, but isothermal compression is not permitted to have an increase in the temperature of the working fluid the sole purpose is to increase the pressure. So, if you are supplying certain amount of work, that will give rise to certain amount of heating. So, that energy will be taken from the gas by the cooling. So, basically for isothermal compression the amount of energy you are supplying in the form of work and the rise in temperature is not permitted. Hence this amount of energy will be taken from the working fluid by cooling. So, this is very important that isothermal compression sole purpose is to raise pressure only.

So, now let us discuss about the compression efficiencies. In one of the previous classes we have talked about isentropic efficiency of the compression as such we had seen that irreversibility is present with the compression process and it is because of that reason isentropic efficiency that is the actual work that should be supplied to the compressor for the compression of the working fluid would be more.

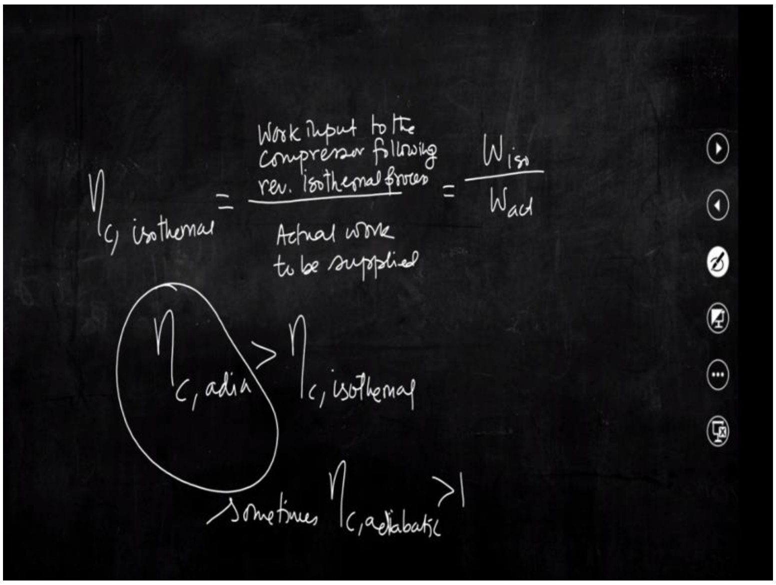
(Refer Slide Time: 15:06)



Now today we shall discuss about you know compression efficiency. So, the first one is you know adiabatic efficiency $\eta_{c,adiabatic}$ is the ratio of work input to the compressor following reversible adiabatic process to Actual work to be supplied to the compressor. So, if we try to recall the T s plane so these are the pressure limits and this is 1, this is 2.

But in reality you know the actual process should be this is 2 and this is 2s. So, if we write here this is actually $\eta_{c,adiabatic} = (h_{2s} - h_1)/W_{actual}$, that means if we apply steady flow energy equation across the compressor then the work needed to be supplied for the compression process is $h_{2s} - h_1$ following isentropic process.

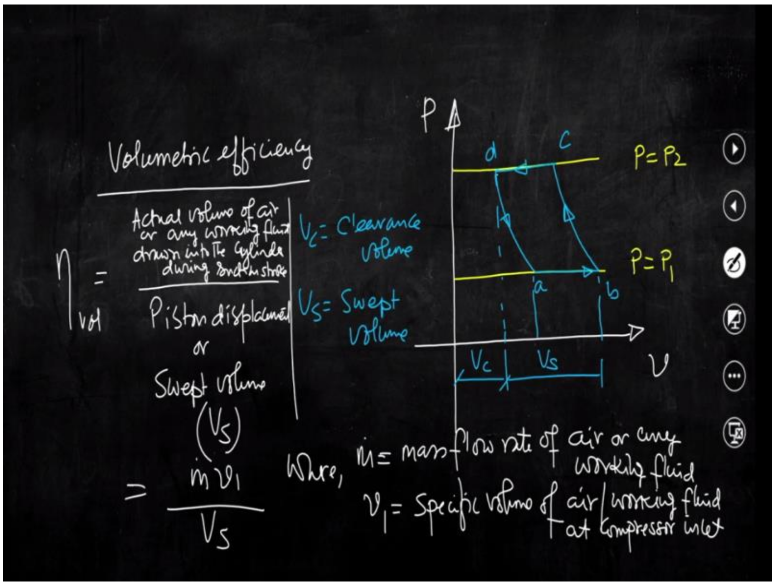
(Refer Slide Time: 17:29)



Similarly, we can write $\eta_{c,isothermal}$. Basically it is the ratio of work input to the compressor following reversible isothermal process and actual work to be supplied. Now, if you recall today, we have discussed that work input following reversible isothermal process is lesser than the work input following reversible adiabatic process.

So, if we assume that $\eta_{c,isothermal} = W_{isothermal}/W_{actual}$. So, $\eta_{c,adiabatic} > \eta_{c,isothermal}$. Now sometimes $\eta_{c,adiabatic}$ is even greater than 1.

(Refer Slide Time: 19:37)



We shall discuss about another efficiency that is called volumetric efficiency of the compressor. So, you know, that if we try to draw process in the Pv plane we are assuming these are two pressure limits p_1 and p_2 and if we consider a to b is suction.

And so this is the clearance volume Vc and this is the swept volume Vs. So, this is basically if you consider this is a reciprocating compressor. Now a to b is the suction stroke and then b to c is the compression process following a reversible adiabatic compression then c to d is the process which is discharging high pressure working fluid to the combustion chamber.

So, then finally process will restart and it will start from a to b. So, a to b is the suction then b to c is the compression and c to d that is the process at which high pressure working fluid is discharged into the combustion chamber. Now question is from this particular diagram we can define what would be the volumetric efficiency.

So, ideally try to understand that this is the swept volume. So, pressure is getting reduced from d to a inside the compressor so basically expansion. So, piston is again coming down and then suction stroke starts. So, this is the swept volume.

And if the piston is now getting displaced between these two locations I should say. So, ideally it is because of this piston movement we are supposed to get the volume of air inside the cylinder which is equal to Vs and that is this swept volume. So, again I am telling you process a to b is the suction stroke, b to c is the compression stroke and when compression stroke ends then that high pressure working fluid will be discharged into the combustion chamber.

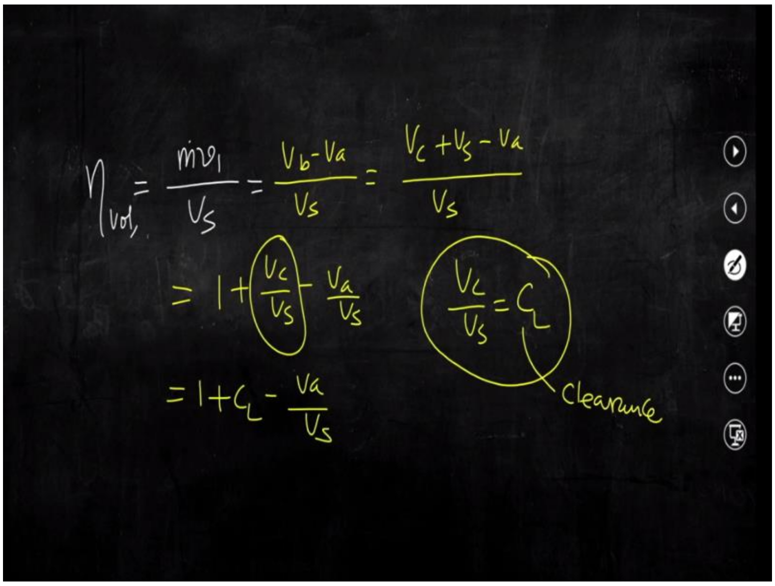
And then when pressure is still at P2, then finally again there is an expansion because piston has to come to the another pressure. So, that is pressure inside the cylinder should be again suction pressure at P1. So, essentially we are trying to have this is the swept volume. Ideally you are supposed to have volume of air that is equal to Vs inside the cylinder.

So, this is the volumetric efficiency that means ideally you are supposed to have this is Vs this amount of or this volume of air inside the cylinder, but we are getting you know another amount of working fluid or air into the cylinder and the ratio of this two is known as volumetric efficiency, certainly actual volume of pair that should be drawn into the cylinder during suction stroke is not equal to the piston displacement or swept volume.

$$\eta_{vol} = \dot{m}v_1/V_s$$

So, $\dot{m}$ is mass flow rate of air or any other working fluid and v_1 is the specific volume of air or any other working fluid at compressor inlet. So, this is the definition of this volumetric efficiency. So, now question is I have drawn this P-v diagram here only to establish another important relation between the geometrical configuration that is swept volume, clearance volume of the compressor and the volumetric efficiency.

(Refer Slide Time: 27:22)



$$\eta_{vol} = \dot{m}v_1/V_s$$

If we try to go back to the previous slide this is the actual volume of air that should be drawn into the cylinder that is $V_b - V_a$, so this is

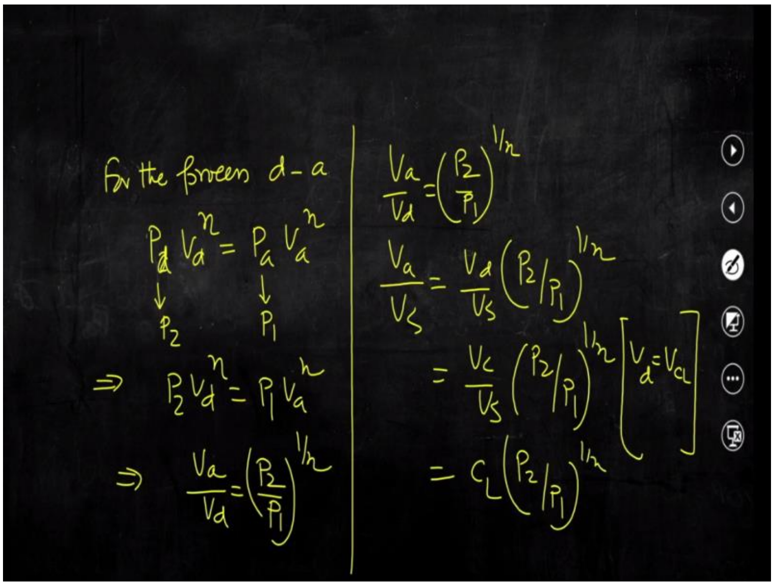
$$\eta_{vol} = \frac{(V_b - V_a)}{V_s} = \frac{V_{CL} + V_s - V_a}{V_s} = 1 + \frac{V_{cL}}{V_s} - \frac{V_a}{V_s} = 1 + C_l - \frac{V_a}{V_s}$$

So the ratio of clearance volume to the swept volume is defined by another term that is called clearance C_L and that is called clearance.

So, we have to relate this $\frac{V_a}{V_s}$ in terms of the pressure ratio and then we can close the expression of this volumetric efficiency. So, if we go back to this, you know, we can write from this expression is that $\frac{V_d}{V_a} = \left(\frac{p_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$.

So, else what we can write you know if we assume that this process is $pv^{\gamma} = C$ or more genetic process if we assume that $pv^n = C$.

(Refer Slide Time: 30:12)

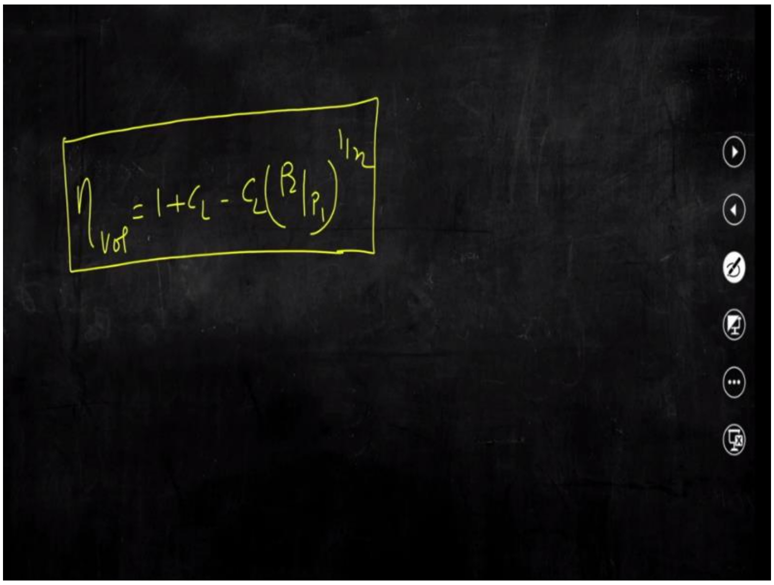


Then what we can write? We can write for the process d to a.

$$p_d V_d^n = p_a V_a^n \rightarrow p_2 V_d^n = p_1 V_a^n \rightarrow \frac{V_a}{V_d} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}$$

$$\frac{V_a}{V_s} = \frac{V_d}{V_s}\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} = \frac{V_{CL}}{V_s}\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} = C_L\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}$$

(Refer Slide Time: 33:39)



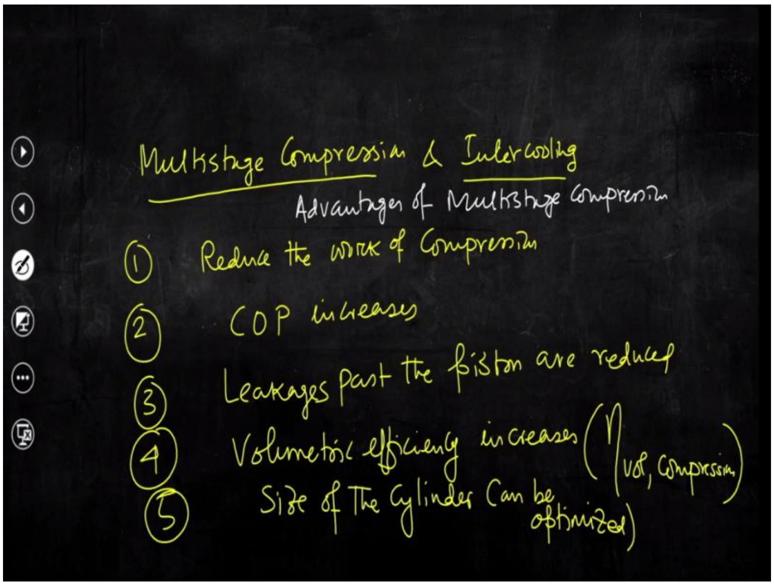
So, we can next write that

$$\eta_{vol} = 1 + C_L - C_L \left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}$$

So, we understand that volumetric efficiency will be reduced if we need more pressure ratio. So, that means if we need to raise high pressure of the working fluid then volumetric efficiency will reduce. What are the possible reason behind it?

I should say the possible reason behind it is the leakage because if we need to raise high pressure of the working fluid through the compression process certainly leakage of the working fluid will be there and hence it will eventually reduce the volumetric efficiency.

(Refer Slide Time: 35:03)



So, with this now let us discuss about the important part of this unit is called multistage compression and intercooling. So, basically if we need to go for multi staging of the compression process intercooling is needed. So. let me tell you one thing why we need to go for multi staging? First of all if we try to recall in the compression process the sole purpose is to raise the pressure with an appreciable increase in density as well as you know increase in temperature as well.

So, basically you know that if we need to increase the pressure as well as temperature when we need to supply compressed air promptly to any combustion chamber, for that we need to go for multi staging compression. I shall be discussing today why we need to go for multi staging and if we need to go for multi staging intercooling is very much essential. So, this coupled keywords multi stage compression and intercooling, these two are basically directly related. If we need to go for multi staging compression we need to go for intercooling. Now as we have discussed that if the compression process is needed only to increase the pressure of the working fluid with no increase in temperature, then multi staging may not be required, but it is very you know unlikely that we will be having a compression process wherein sole purpose will be to increase substantial amount of pressure without increasing temperature.

Otherwise isothermal compression will not be possible. So, if we need to increase the pressure so if we go back to the previous slide we can see that if we need to increase pressure from P1 to P2 then we can understand that pressure ratio r_p that we could define in the last class, so for such a increase in high pressure if the requirement is not only to increase pressure but also to increase temperature, you know, temperature of the working fluid at the end of the compressor will be so high that temperature will be having some detrimental effects for the mechanical component of the compressor. Now that is one thing. Second thing you know that means multi staging is needed if we need to increase the pressure of the working fluid substantially.

Then instead of a single stage compression we need to go for multi stage compression, why? Because multi staging compression would provide a few distinctive advantages feature.
Now we also can increase that pressure using a single compression or single stage compression, but if we perform a single stage compression to develop such a high pressure then whatever points I am writing here all these advantages features will not be there. So, that means the work of compression will be more.

So, the compression work would be more, but if we use multi stage compression then that multi staging reduce the work of compression. Number two coefficient of performance increases, few minutes back I said here that sometimes adiabatic compression efficiency becomes greater than 1.

Efficiency cannot be greater than one then we need to define coefficient of performance. So, the coefficient of performance will be more if we use multi stage compression, but again I am telling you have to be very careful that all these points we are discussing here only when we are comparing the compression process that is multi stage compression vis-a-vis single stage compression.

If we need to increase a substantial pressure of the working fluid then if we go for single stage compression all this favorable aspects or advantages features will not be there. COP increase and leakages past the pistons are reduced and volumetric efficiency increases of course.

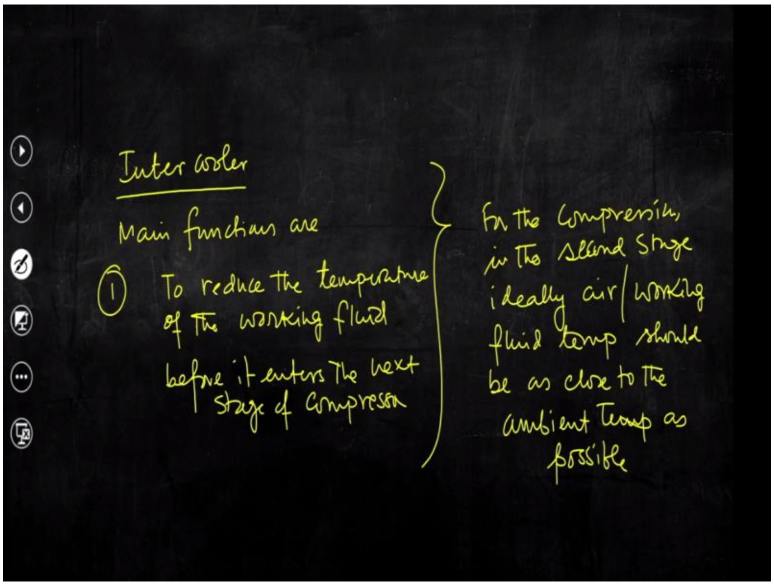
So, this volumetric efficiency will increase, size of the cylinder can be optimized. See few minutes back we have discussed that volumetric efficiency is function of pressure ratio if this pressure ratio $r_p = \frac{p_2}{p_1}$ is very high then volumetric efficiency will reduce, but if we use instead the multi stage compression then volumetric efficiency will increase.

Otherwise it will reduce. Again I am telling we need higher compression ratio that is P_2 would be more. So, now question is for this multi stage compression again as we have discussed that the sole objective is to increase high pressure of the working fluid with an appreciable increase in temperature even we need to go for multi stage compression an important aspect of the multi stage compression is to use an intercooler.

Why because as I said you that at the end of the compression process pressure will certainly increase, but along with the pressure temperature of the working fluid also will increase and if the temperature increases beyond a threshold value that particularly high temperature working fluid will be having detrimental effects on the mechanical component of the compressor.

Second thing it is easier to compress you know heavier cold air or any other gas rather than hot air. So, accounting for this intercooler is placed between two compressors if we need to go for multi stage compression.

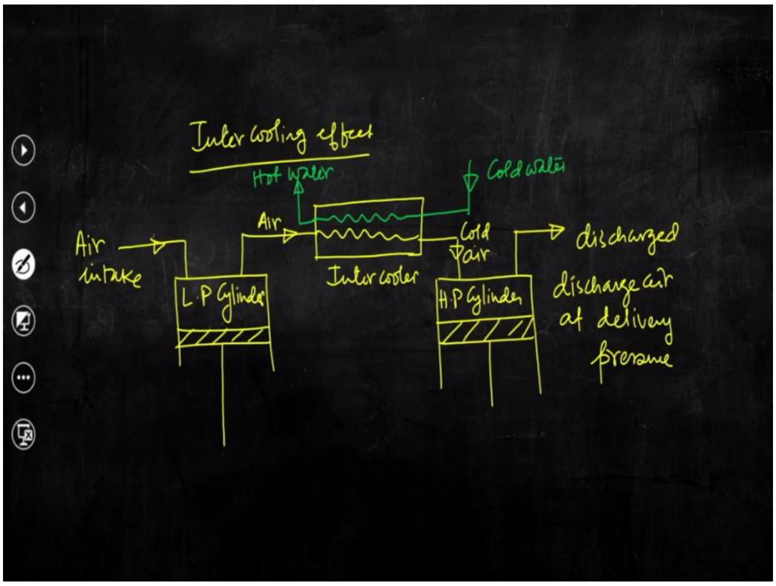
(Refer Slide Time: 45:47)



So, I am writing here intercooler, its main function are to reduce temperature of the working fluid before it enters the next stage of compressor. Actually if we need multi stage compression the working fluid that comes out from the first stage or first compressor will be having high pressure and high temperature. Ideally inlet temperature of the working fluid of this, or temperature of the working fluid at the inlet of the second compressor ideally should be equal to very low and as close as the ambient temperature, but for that this intercooler is used. So, I am writing here that for the compression in the second stage, ideally air or working fluid temperature should be as close as to the ambient temperature as possible.

It is very difficult to bring the temperature of the working fluid equal to the ambient temperature, but our objective should be to bring or to reduce the temperature of the working fluid before it enters into the second stage of compression closer to the ambient temperature. So, this is why intercooling or intercoolers are placed and second thing you know that as I said you that it is an easier to compress cold heavier air than hot air and temperature will certainly increase and if temperature increases beyond a threshold value then that high temperature will be very much difficult to handle by several mechanical components those are they are inside the compressor. So, with this now let us just schematically discuss about this intercooling effect.

(Refer Slide Time: 49:49)



So, I am writing here intercooling effect. So, if we consider air is coming, then air is taken to another mechanical component, then that air is taken to another compressor. So, basically you know that is air intake, so this is low pressure cylinder, this is high pressure cylinder and so air is first taken into this low pressure cylinder. It is now compressed.

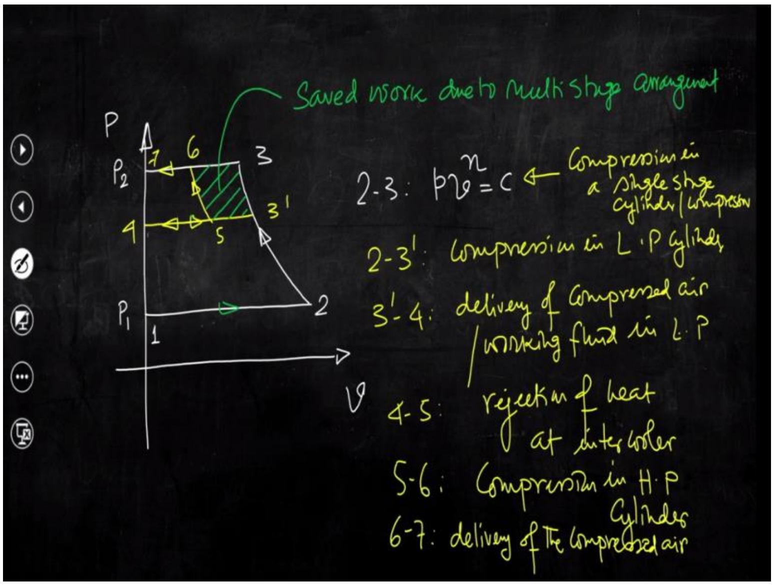
And that air which is coming out from the low pressure cylinder is now taken in this intercooler. So, this is intercooler and inside the intercooler that air releases heat, but we need to maintain that pressure will be equal to either the low pressure cylinder or a pressure which is in between these two cylinder pressures. So, we will be discussing today on that aspect and then that air is again taken to high pressure cylinder and again further compressed.

So, this is basically you know cold air and finally that air is discharged and this discharged air is at delivery pressure. So, now question is we need to reduce the temperature of the air before it enters into the second stage of turbine. As I said you few minutes back what is done here you know that here cold water is allowed to pass through this intercooler and this is hot water.

So, basically you know that air releases heat to this water stream, water temperature increases. By releasing heat, we can reduce the temperature of air before it enters into the second cylinder or second compressor. As I said you ideally it should be very much favorable for the compression process of course if we can reduce the temperature of the air as close as to the ambient temperature.

But it is not really possible but we need to reduce the temperature and finally the air will be again compressed and it will be discharged at the delivery point. Now as I said you that this cooling should takes place at a pressure which is developed by the first cylinder or it should be in between a pressure which is in between the pressure developed by the first cylinder and pressure that would be developed by the second cylinder so that will be an intermediate spacer stage. So, this is basically intercooling effect.

(Refer Slide Time: 54:14)



Now, if you try to map the processes in Pv plane, then we can see that so this is P equal to P_1 and say this is P equal to P_2. So, we need to increase pressure of the working fluid from P_1 to P_2. There is one case that if we use a single stage compression then we certainly can develop the pressure from here. So, this is 2 say this is point 1 and this is 3 and 2 to 3 say this is $pv^n = C$.

Now, if we increase the pressure using a single stage those problematic issues will be there, reduction in volumetric efficiency, reduction in COP, work input will be more and the rise in temperature at the end of the compression process should be so high that high temperature of the working fluid will have detrimental effect on the mechanical components of the pump pressure.

What is done here now say, for example, now it is compressed in the first cylinder up to an intermediate pressure say this is the intermediate pressure 3′ and then it is so process 2 to 3′ that is basically compression in low pressure cylinder and this is compression single stage cylinder or compressor then what is done 3′ to 4 that is delivery of compressed air in low pressure. Then finally again we should be having another process that is 4 to 5 and say this is the point and this is point 5. So, 4 to 5 that is basically you know rejection of heat at intercooler and then 5 to 6 that would be compression at high pressure cylinder.

So, finally 6 to 7 that is delivery of compressed air. So, what you can understand from this particular diagram is that this is the amount of work which we do not require because of this multi stage compression. So, we are allowing compression process from 2 to 3′ in low pressure stage compressor then 3′ to 4 that is delivery of compressed air or working fluid in low pressure.

Then 4 to 5 is essentially again release of heat from the compressed air to another fluid inside the intercooler and finally 5 to 6 that is again rise in pressure of the working fluid in a high pressure compressor. So, had we performed the compression process by using a single stage compressor certainly the pressure at the end of the compression would have been P2.

So, our objective is to rise the pressure from P1 to P2 so there are two possibilities one is that we can use a single stage compressor following this process 2 to 3. In another case what we are doing we are using multi stage compression, we are developing pressure from 2 to 3′ first then by having certain another mechanical arrangements we are developing pressure from again intermediate pressure to the final pressure.

But in that case what we are doing we are saving this much amount of work. So, this is saved work due to multi stage arrangement. Had not we performed the compression process by using multi stage compression, we would have certainly got pressure at the end of the compression that is P2, but in that case this much amount of additional work would have been needed to be supplied to the compression.

So, this much amount of additional work would have been needed had we perform the compression process by using a single stage compressor, but what we can do, now we can save this much amount of work because of this multi staging arrangement, but mind it for this multi staging arrangement we can save this much amount of work that is true that will certainly increase the cycle efficiency.

But what is most important that you know we need to have an important mechanical component or mechanical arrangement that is intercooler. So, what we need to do we need to supply again a coolant that will take away certain amount of energy from the flowing gas or air or any other working fluid. To have such an arrangement, the system will be bulky and for that both operational cost as well as maintenance cost would be there.

Second thing it is because of this reduction in temperature of this working fluid inside the intercooler though we are getting certain amount of benefit in terms of work needed to be supplied to the compressor and that is this much amount, but the cycle efficiency is net work output by net energy input.

So, what will happen you know instead of having an increase in the cycle efficiency eventual impact would be a reduction in cycle efficiency. So, multi stage compression with intercooling is needed because we need to run the unit for a long time and for that we need to ensure that even if we need to compromise with the cycle efficiency, but at least we can run the unit without inviting additional problems like failure of mechanical component because of the rise in temperature and many thing others.

So, to summarize today's discussion we have discussed about the compression processes and work needed to be supplied to the compressor for the compression process following reversible adiabatic, reversible isothermal and reversible poly tropic processes then we have discussed about several efficiencies of the compression process. Finally, we have discussed about the requirement of multi stage compression and for the multi stage compression we had seen that intercooling is very much essential.

And if we need to go for multi stage compression certainly intercooling will be there, but this arrangement eventually reduces the cycle efficiency. We stop here today and we shall continue our discussion in the next class. Thank you.