Applied Thermodynamics for Engineers

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Lecture – 11
Air Standard Cycles

Good morning everyone, welcome to week number 4, where we are going to talk about the air standard cycles. Over the last two weeks, we have discussed about the fundamentals of thermodynamics or basically we have reviewed the fundamentals of thermodynamics in week number 1. Then we have discussed about the property relations where we have understood how to estimate the changes in some important properties like internal energy or enthalpy or entropy in terms of the properties which can be directly be measured like temperature, pressure and specific volume.

And then in the third week, we have discussed about the properties of pure substance both in terms of the use of thermodynamics property tables and also in terms of the ideal and real gas equation of states. So, now you in a position to analyse thermodynamic processes and therefore thermodynamic cycles. Thermodynamic power cycles which are the way of converting thermal energy to useful work output or the refrigeration cycles which are in a way of converting some work input into form of thermal energy needs to be discussed in different modules. And the first one that we have in our scope is the air standard cycle or the group of cycles which we are going to call the air standard cycles.

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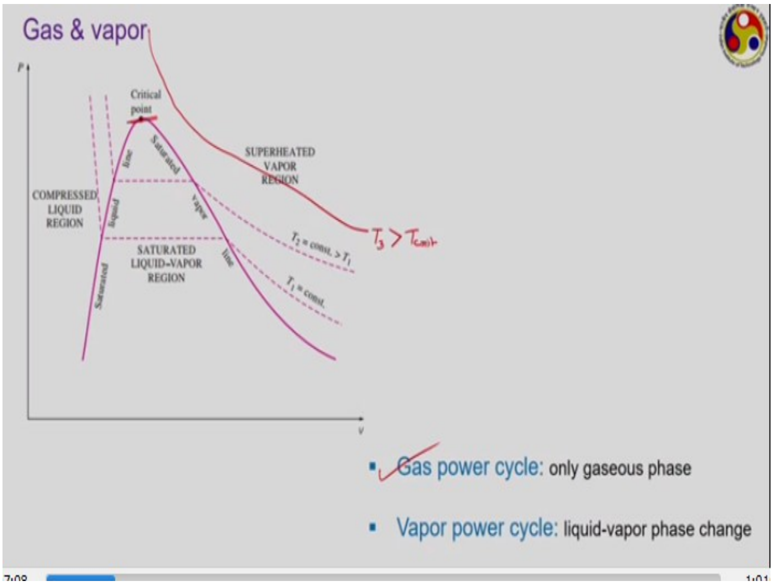

So, in air standard cycles, before going into the details of the term air standard cycles, I would like to go back to this particular diagram which you have definitely seen in the previous week. We just see this simple *Pv* diagram of the liquid vapour phase change process, there we can clearly see there are three different regions; the compressed liquid region, the saturated liquid-vapour mixture region and the superheated vapour region.

And your substance can exist in any of the region depending upon the property values and by now, you know how to understand or how to identify the regime for a given state and then how to get the corresponding property values in term using the corresponding tables; thermodynamic property tables. But one important distinction that we probably have discussed that is between the gas and vapour that also you can identify in terms of this particular diagram.

Like here we have a critical point so, we know that when we are talking about a substance which is below its critical point then, just by compressing the substance for maintain at a temperature below critical temperature, we can convert it to from vapour to liquid phase. Like just look at that two constant temperature lines shown here, if suppose, we start with a point somewhere here, maintain the temperature T_1. And then following this constant temperature line, if we keep on increasing the pressure or reduce a volume then, you can clearly see that it is moving along this particular line. So, it is initially superheated vapour gradually, it approaches the saturated vapour state here then, we further attempt to increase the pressure, there is no change in pressure but drastic change in the specific volume because the vapour state starts to get converted to the liquid state. The phase change continues to attain this particular point for it attains the saturated liquid state and then with further compression, it keeps on going along this particular line where it is liquid but pressure keeps on increasing. Therefore, maintaining a constant temperature simply by pressurising or by increasing the pressure, we can convert a vapour state to a liquid state.

But that is possible only when this constant temperature is below your critical temperature. When we are trying to do the same thing for a temperature value which is higher than the critical temperature, then you will be getting a line somewhat like this. That here we are talking about some temperature T_3, which is a higher than the critical temperature. As this temperature is higher than the critical temperature, despite the continuous increase in pressure, it will never come in contact with the saturated vapour line and therefore, there will be no distinct change in phase, it will be like a single-phase medium throughout. So when are talking about a situation beyond the critical temperature, then by simple compression we can convert a substance or a gaseous substance to corresponding the liquid version and hence we cannot get a phase change going whereas, when the temperature is higher than critical temperature, the gaseous phase can be considered to be non-condensable.

Whereas, when the temperature is lower than critical temperature, it is a condensable thing. And that is why when the temperature of the substance is below the critical temperature, we generally call in vapour, the gaseous phase, whereas, we call it gas, when the temperature is above the critical temperature. And depending upon whether we are talking about so called gas or so called vapour, we can have two kinds of power cycles which can be classified like this.

The first one is the gas power cycle, where throughout the cycle the gaseous phase is maintained. Invariably, the substance will be maintained at a temperature will above its critical temperature so that it never attends any situation very close to the phase change. Substances like oxygen or hydrogen etc., under normal atmospheric condition remains well above the critical temperature and therefore, whenever we are using them under any kind of thermodynamic cycles that invariably will have only the gaseous phase.

We shall be calling them gas power cycles, like air is the most prominent example which is its primarily a mixture of oxygen and nitrogen and despite being a mixture, we often considered air as the single medium. And that is why using air also, we can have gas power cycles whereas, the other one is the vapour power cycle, where the condition or temperature levels will invariably be less than the critical temperature, so that, by simply compressing, we can convert the vapour phase to the liquid phase. So, the vapour power cycles will generally involve a liquid vapour phase change process or I should say two processes; one where the vapour gets converted to liquid that is condensation whereas, another one when the liquid gets converted to vapour that is evaporation. So, during gas power cycle, we have to deal with only a single phase which is a gaseous one. Whereas, in vapour power cycle, we have to deal with both liquid and vapour phases and also the phase change processes, both evaporation and condensation.

Now, in this particularly, the kind of cycles that we are going to talk about those are actually gas power cycles, where we shall be maintaining the gaseous phase. So, generally the working temperature levels will be well above the critical temperature of the corresponding substance or corresponding fluid and therefore, we do not have to bother about any kind of phase change. So, though we have given the title of the module as air standard cycles but we can also call them the gas power cycles.

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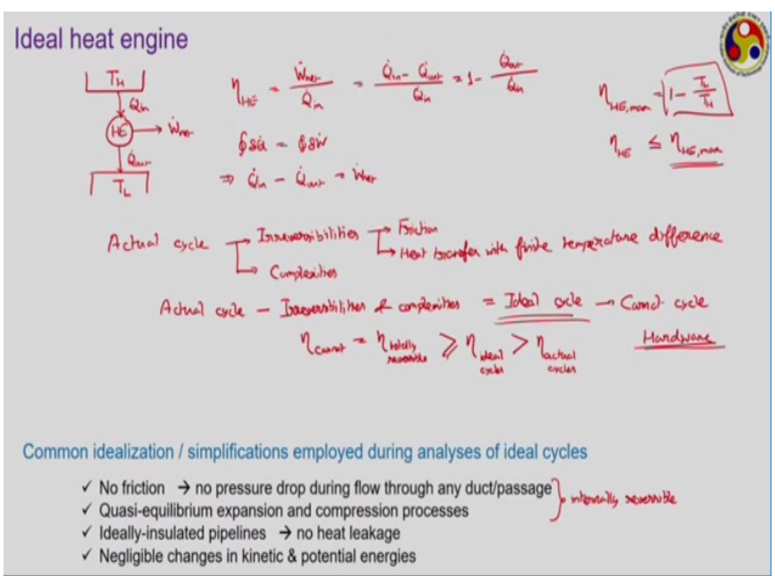

Now, whenever we are looking to produce power, mechanical power or work output in by providing some thermal energy as an input, we have the term heat engine which was defined in conjunction with a second law of thermodynamics. If it was a simple schematic representation of a heat engine which we have done earlier also, if this is your heat engine which is working between two constant temperature reservoirs. This is the high temperature reservoir T_H, this is a low temperature reservoir, T_L. The heat engine is receiving some Q_{in} amount of heat from the high temperature reservoir, rejecting some Q_{out} amount of heat to the low temperature reservoir and only a fraction of this Q is getting converted to W work output or net work output. As per the second law of thermodynamics, we know that it is never possible to convert 100% of the input thermal energy to work output and also some Q_{out} will always be present.

Second law of thermodynamics also gives an upper limit of this value of this W unit in terms of the T_H and T_L. Now, for any heat engine, the efficiency can be defined as the network output that we are getting from the cycle divided by thermal energy input that has been given to attain that particular work output. The mathematical representation is as follows:

$$\eta_{HE} = \frac{W_{net}}{Q_{in}}$$

Or as per the first law of thermodynamics applied over a cycle, we can always write:

$$\oint \delta Q = \oint \delta W$$

Generally, this, we are talking about a cycle which keeps on working continuously therefore, instead of writing in terms of heat and work, we generally prefer to write them in terms of rate that is the heat transfer rate and work transfer rate.

$$\oint \delta \dot{Q} = \oint \delta \dot{W}$$

Accordingly, the efficiency will be:

$$\eta_{HE} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

here this dot represents per unit time that is a rate. So, following the first law, it is:

$$\oint \delta \dot{Q} = \oint \delta \dot{W}$$

for the heat engine, so we have:

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{W}_{net}$$

Q_{in} *dot* that is being supplied

Q_{out} *dot* that has been taken out from the system

As per our conversion, heat supplied to the system is positive whereas, work done by the system is positive so, here work done by the system is net work done.

So, if we replace this form of first law in the efficiency expression then we have:

$$\eta_{HE} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

So, we can easily calculate the efficiency or work output of any heat engine just from the knowledge of these two energies i.e., these two hear transfer I should say. Now, if this heat engine is a reversible one then, we know that the maximum possible efficiency this heat engine can have is a corresponding Carnot cycle efficiency which is given as:

$$\eta_{HE,max} = 1 - \frac{T_L}{T_H}$$

where both these temperatures T_L and T_H are absolute temperature because following the Carnot postulate, we have or following may be the Joules postulate I should say we can write:

$$\frac{Q_{out}}{Q_{in}} = \frac{T_L}{T_H}$$

from there we get this particular expression for the efficiency or maximum efficiency.

For any real heat engine, the efficiency will be:

$$\eta_{HE} \leq \eta_{HE,max}$$

it will be = the maximum 1 when you are talking about a reversible cycle like a Carnot cycle otherwise, it will always be less than this.

But now when you are talking about a reversible cycle, the cycle has to be both internally and externally reversible. Internally reversible means, there is no friction, there is no unconstrained expansion or compression. Whereas, externally reversible means, I am sure you remember, external reversible means there is no heat transfer process which involves finite temperature difference between the system and the surrounding.

Even if there is any heat transfer taking place that has to takes place over an infinitesimally small temperature difference between systems and surrounding. So only when the system is both or I should say the cycle is both internally and externally reversible, we can achieve this particular efficiency expression. Now this thing we already know now, for practical cycles or actual cycles it is never possible to attain this particular maximum efficiency. Because in actual cycles, we can have several kinds of losses. Let me write actual cycle, there can be the presence of several irreversibilities, commonly irreversibilities being friction and heat transfer with finite temperature difference. These are the two most common type of irreversibilities which are always present in any practical engines because friction you can never avoid, friction will always be there and friction is always a loss.

Because simply think about if you rub our hands, one on top of the other, whenever my right hand is moving like this in the upward direction, the friction is opposing the motion. Now, when it is coming back in this, friction is again opposing the motion, so friction is always a loss, friction is never help in terms of work output or rather I should say friction always causes us to lose a part of the actual work produced by the system.

Similarly, presence of a heat transfer in finite temperature difference leads to irreversibilities but along with irreversibilities, we can also have several practical complexities in the engine. Practical complexities means the way we are drawing, it is never possible to have heat transfers done this with way, means, practically it is never possible that we are taking the heat engine first in contact with the high temperature reservoir getting heat from this.

And then again, when required taking in contact with the low temperature reservoir and achieving the heat loss because practically, always have to provide some options for a some kind of dark or contact surfaces etc., which will lead to additional design complexities and all such complexities, the presence of pipe bends etc., presence of different expanding or contracting channels they will all lead to losses.

So, in actual cycles we can have all these kinds of losses, some of this losses we shall be discussing as a part of our next module, in week number 5. But here because of the presence of this irreversibilities and complexities, the efficiency of an actual cycle is always inferior to the efficiency of the ideal cycles, which is a Carnot cycle. Somehow, if it is possible that from the actual cycle performance or actual cycle behaviour, we can subtract all these irreversibilities and the design level complexities.

Then what we achieve is an ideal cycle? So, an ideal cycle is the one which does not involve any irreversibilities, so that is irreversible in nature and also here, we are neglecting all kind of design level complexities, so that we can visualise the heat transfers to takes place just the way they have been drawn here, then only we talk about an ideal cycle. Remember this is only an idealisation practically, all cycles are real cycles with irreversibilities and complexities.

But they will become extremely difficult to analyse from thermodynamic point of view or from any theoretical point of view. And therefore, what we can analyse in reality is only this ideal cycle. Then once we know the behaviour of the ideal cycle then, we may perform some experiment with the actual cycle and try to identify what are the possible kinds of losses. That means once we know for a given situations what kind of work output or efficiency we can get from an ideal cycle, then we can subtract the losses because of the irreversibilities, from there, we can get the performance of the actual cycle as well. So, the ideal cycles are simple cycles which allows the also, studying the effect of major parameters. Now, the question that must be coming to your mind is why you are studying the ideal cycles, as they never exist in reality. Issue is that in an actual cycle, there are so many parameters which are acting together, which is not present in ideal cycle.

Or I should say an ideal cycle allows us to identify the effect of each relevant parameter separately. Now, once we know that what is the effect of one particular parameter on the efficiency of an ideal cycle, that particular parameter is going to affect the efficiency of the actual cycle in the same way. The magnitude may be different but the term should be same. Like suppose if we can identify one parameter such that increasing the value of this parameter will cause an increase in the efficiency of the ideal cycle.

Then for actual cycle also increasing that parameter will increase the efficiency. Now, the level of increase in the efficiency may be smaller in case of actual cycle but it will never possible that the increase in that parameter in cause an increase in the ideal cycle but a decrease in the actual cycle efficiency, that will always be of the same way. So, ideal cycles or the concept of ideal cycles allows us to study the effect of all relevant parameters individually, so that we can directly extrapolate them to the actual cycles and thereby identifying the options of increasing or improving the performance of an actual cycle.

Now, the best example of an ideal cycle is the Carnot cycle, the only cycle that you know till now, which we introduced in the first week itself in conjunction, in the second law of thermodynamics cycle. The Carnot is a cycle which involves four processes. All are perfectly reversible, both internally and externally, two of them are adiabatic or I should say isentropic and two of them are reversible isothermal. So Carnot cycle is a most ideal cycle that is possible then, next question is once you already know the Carnot cycle, then why you need to define a other kind of ideal cycles. Because while in Carnot cycle, we can have two isentropic and two isothermal processes, but it is also possible to define or conceptualise ideal cycles which involves different other kind of processes.

Then, why you need to know all these ideal processes? The problem which necessities the definition of other ideal cycles are related to the hardware or I mean the actual working procedure of real engines. The way actual real engines work that will shall be seen shortly; they can never be visualised to be something similar to the Carnot cycle. And because of this hardware issues, we have to do the attempt of developing new ideal cycle which suits the actual performance of an engine closely which is not possible with Carnot cycle.

That is why we have to define different other kinds of ideal cycles; it was associated with the gas power cycles which we shall be doing in this particular module. Practical cycles, of course differ significantly in terms of the hardware for compared with the Carnot cycle and that is why we need this ideal cycle. One important point that we have to remember for this ideal cycle is that, these ideal cycles are internally reversible but not necessarily externally reversible. That means, they are frictionless, there is no sudden expansion or contraction that is happening but they may involve heat transfer with finite temperature difference. Because practically, if we want to have heat transfer with infinitesimally small temperature difference, either you have to provide infinitely large area or we have to provide infinite time both of which are practically impossible.

Because if we have to provide very large area, then the size of the instrument will be extremely huge whereas, if we want to provide sufficient amount of time then the cycle will be extremely slow to deal with. And that is why the cycles that we are going to talk about here the air standard cycles or gas power cycles, they are internally reversible but not necessarily externally reversible. Then, what we are going to talk here is efficiency of Carnot cycle.

Or I can write the efficiency of a totally reversible cycle is the highest, as given by this particular relation:

$$\eta_{Carnot} = \eta_{totally\ \ reversible}$$

For an ideal cycle, the efficiency may be lower than this because they may involve external irreversibility, they are internally reversible but may not be externally. That means, it is very much possible that the cycles are internally reversible but externally irreversible as they are going to involve heat transfer in finite temperature difference.

And because of the presence of this externally reversibility, the efficiency of this ideal cycles will be lower than the corresponding efficiency of a Carnot cycle or a totally reversible cycle. And then the efficiency of this ideal cycles they will be even greater than the efficiency of the actual cycles.

$$\eta_{Carnot} = \eta_{totally\ \ reversible} \geq \eta_{ideal\ \ cycles} > \eta_{actual\ \ cycles}$$

So, we are going to develop or conceptualise different kind of ideal cycles to suit the working procedure of different kind of real engines. And then the developed expressions for their work output and efficiency, so that we can get an idea in which direction the efficiency of an actual cycle should go by doing different kind of parametric variation. So, the common idealisation and simplification is that we are going to consider during the analysis of this ideal cycles, the first is no friction therefore, no pressure drop during flow through any duct or passage.

The cycles are going to be internally reversible, the second is quasi-equilibrium expansion and compression processes, no sudden expansion or compression, as we are considering these two assumptions, so the cycles are as I have mentioned internally reversible. But we are not putting any condition of having heat transfer only with infinitesimally small temperature difference, so the cycles can be externally reversible.

Then, we are assuming ideally insulated pipelines, so that there is no heat leakage from system to surrounding or from surrounding to system. Heat transfer will take place only in the sections of the cycle, where it wants it transfer to take place. And also, we are generally going to neglect the changes in kinetic and potential energies which is not a very bad assumption, because in devices which involves some kind of shaft work like turbines, compressors, pumps, there the magnitude of shaft work generally extremely large compared to the changes in kinetic and potential energies.

Similarly, the device which does not involve shaft work like a boilers, condensers, etc., there the changes in the enthalpy of the substances is so large that the changes in kinetic and potential energies can again be neglected there. Only in devices like nozzles or diffuser, we have to consider the changes in kinetic and potential energies which are of course, not relevant to heat engines.

But we have to remember that in nozzles or diffusers are objective is to cause a change in the kinetic energy and that is why, the changes in kinetic energy is significant. Otherwise, like in the analysis of heat engines, we generally do not have to consider the changes in kinetic and potential energies. If possible, I would like to show you some examples later on, you may often find that the changes in enthalpy is so large that the changes in kinetic energy may be well below 1% of the changes in enthalpy. Similarly, the changes in potential energy can be will below 0.1% compared to the changes in enthalpy and that is why we often neglect them.

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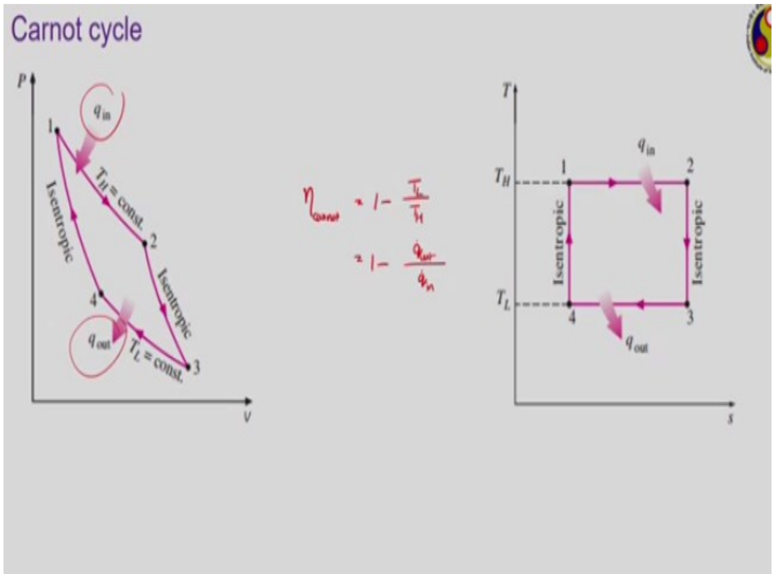

Now, this is a Carnot cycle which is the most ideal cycle that we can have. This is totally reversible cycle comprising of four processes; two isentropic processes like shown by process 2 to 3 and 4 to 1 in this diagram and two isothermal processes, in process 1 to 2 heat is being supplied from a reservoir maintained at a temperature T_H or infinitesimally small temperature higher than T_H, it add this q_{in} amount of heat.

Similarly, in during the process 3 to 4, the system is allowed to come in contact with a reservoir maintained at a temperature slightly lower infinitesimally small, this amount lower than the temperature T_L, thereby facilitating this amount of heat loss; $q_{\text{dot out}}$. This is the corresponding *Ts* diagram. Now *Ts* diagram is always very important because you may feel that the *Pv* diagram is sufficient to know the work output. That is correct.

You know that; you are absolutely correct because the area influenced by the *Pv* diagram gives you the net work output from the cycle. Or if are interested to know work associated with any particular process, you can just take the area under the particular curve. Then, why we need the *Ts* diagram? Because like we have seen to calculate the net work output or to calculate the efficiency, we never have to bother about the actual work that is going on.

We can just stick to the heat transfers and from there, we can get the magnitude of the work output or efficiency. Another big advantage is that, all we are assuming the Carnot cycle or any other ideal cycles that we are going to talk about to be internally reversible; internally reversible means there is no friction. Now, if there is any kind of frictionless adiabatic process to be considered then that has to be isentropic. And therefore, all the isentropic process or I should say all the adiabatic processes can be presented by constant entropy lines that is by vertical lines.

Another important concept to be considered here is that we know that entropy change of a system can takes place by two ways: First one is along with heat transfer, what is a direction of heat transfer; there will always be entropy transfer in the same direction. And second is the presence of internal irreversible, it is like friction. Now, as per the assumption that we have put forward in the previous slide, there are no internal irreversiblities, so this is not there. Then, entropy change will take place only when there is heat transfer and also the change in entropy will follow change in the direction of heat transfer, or I should say the heat transfer will take place only in the direction of increasing entropy.

That is why *Ts* diagrams often give us good idea about the direction of heat transfer. Like look at the diagram, you can clearly see 4 to 1 is a vertical line, so that has to be an isentropic process, no heat transfer. Whereas during process 1 to 2, the entropy increases so, heat must be added to the system. Similarly, during process 3 to 4, the entropy is decreasing so, heat must be going away from the system, thereby it gives you the direction of heat transfer as well.

So, for the Carnot cycle we know that efficiency of the Carnot cycle is:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

or we can also write:

$$= 1 - \frac{\dot{q}_{out}}{\dot{q}_{in}}$$

Now, practically, it is never possible to devise a Carnot cycle. Why? This is what I am going to show here. But once we are conceptualised, that cycle can be realised in practice either in an open cycle mode or in a closed cycle mode.

Closed cycle mode means, all the processes associated with the cycle will be done inside the same device, there will be no inflow or outflow involved, like ideal reciprocating engines.

Whereas, open cycle mode refers to each of the processes involved in a cycle will takes place in a different device and already devices are connected, so that the system will be restored back to its initial point at the end of the final device.

The steam power cycles generally work in this open cycle mode. The steam power cycles or gas turbine cycles can be good examples of the open cycle mode. Whereas, the reciprocating cycles or the air standard cycles which we are talking here, they are generally are good examples of the closed cycle mode.

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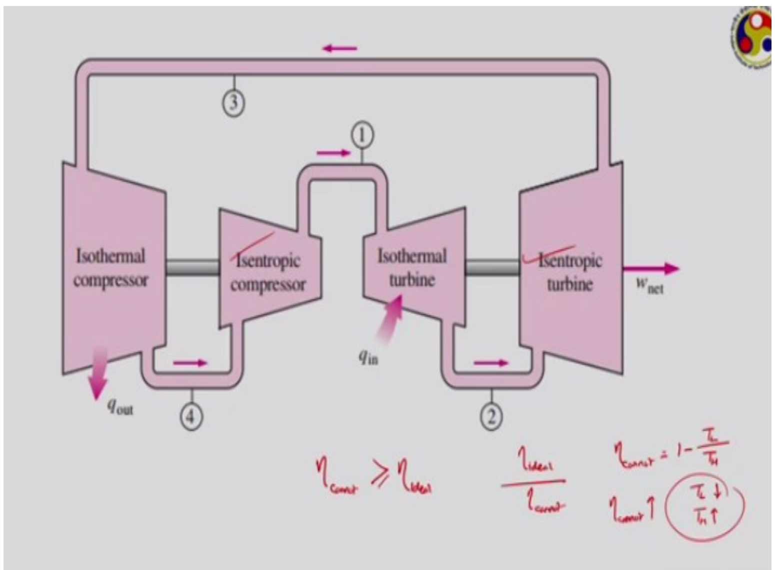

Now, this is one example of how we can achieve the Carnot cycle in an open cycle mode. First the process 4 to 1 is an isentropic compression process during which there is an increase in the temperature but no change in entropy. During process want to do then, we have the isothermal turbine where heat is being added to the system then, 2 to 3 is isentropic turbine, entropy remains constant but expansion goes on so, temperature decreases.

And finally, 3 to 4, we have the isothermal compressor during which heat is being rejected to the surrounding. Now, isentropic processes can almost be achieved in practice provided you can achieve in an ideal insulation and also you can minimise the frictional effects. So, it is somewhat possible to reach very close to the isentropic compression and isentropic expansion processes. However, isothermal heat transfer processes are almost impossible to have in practice.

As I have mentioned, they require either infinite surface area or infinite amount of time to execute the cycle. And that is why isothermal turbines and isothermal compressors are extremely difficult to realise in practice. And that is why we cannot have a Carnot cycle in a practical application, but still Carnot cycle is important to provide or act as the standard with respect to which all the ideal cycles has to be considered.

That is as we have written we always know that the efficiency of the Carnot cycle will be greater than the efficiency of all these ideal cycles that we are going to talk about now, because they involve externally irreversibility. But how close the efficiency of this ideal cycle to the Carnot cycle i.e., if we define a ratio something like:

$$\frac{\eta_{ideal}}{\eta_{Carnot}}$$

Then, when this ratio is 1, then your ideal cycle also be as very close to the Carnot cycle. Whereas, when it is far away from 1, much lesser than 1, then the cycle despite it being an ideal cycle, its performance is not proper. Now, another idea that we can get from this Carnot cycle is that:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

where

T_L is the temperature at which heat rejection takes place

T_H is the temperature at which heat addition takes place

Now, that trend that is if we want to increase the efficiency of the Carnot cycle, what we have to do in terms of T_L and T_H? If T_L increases, then what will happen? If T_L increases, the value of the second term T_L / T_H that increases so, Carnot cycle efficiency reduces. So, to increase the Carnot cycle efficiency, we have to reduce the values of T_L and similar, you have to increase the value of T_H.

That is the temperature correspondent to heat reaction must go lower, whereas the temperature correspond to heat addition must keep on increasing. And that is true for ideal cycle as well, that is the average temperature of heat addition must be higher whereas the average temperature corresponding to heat rejection must be lower. And therefore, even in real engines also, we always keep on or always attempt to increase the average temperature of heat addition, so that the efficiency increases or try to reduce the average temperature corresponding to heat rejection. Of course, there has to be certain kind of limit like the maximum heat addition temperature that we can achieve depends on the material consideration i.e., how much energy or how much temperature your material can sustain. Similarly, the lowest practicable limit of the temperature of heat rejection is the surrounding temperature.

Because if you want to go below surrounding temperature, we have to put a refrigerator into action. But still this trend holds i.e., to increase the efficiency of any ideal or actual engines, we have to increase the average temperature of heat addition and reduce the average temperature of heat rejection.

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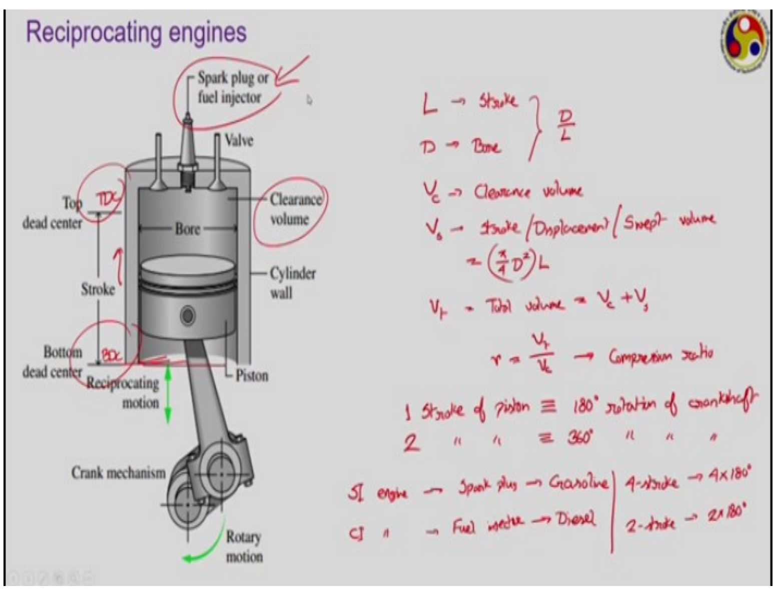

Now, we come to the reciprocating engines, reciprocating engines are the application zones of this gas power cycles or air standard cycles. Just as very simplest schematic diagram of reciprocating engines is shown. Here we have piston so, this is the wall of the cylinder inside which we have this piston having circular cross section as shown in the diagram. This piston can move up and down inside the cylinder to facilitate such kind of reciprocating motion, we have the crank mechanism.

Here we have a crankshaft in this position which rotates and the crank which is connected to the crankshaft that converts this rotary motion to reciprocating motion, thereby the piston can move up and down inside the cylinder. Now, the highest possible position the piston can achieve is called this top dead centre, this is the highest possible level the piston can reach whereas, this is the lowest possible level the piston can reach which is called the bottom dead centre.

Or in short, we call them *TDC*; top dead centre and we call them *BDC*; the bottom dead centre. They are called dead centres because their locations where the velocity of the piston reverses. Like when the piston is moving from bottom dead centre to top dead centre, its velocity keeps on reducing as it approaches the top dead centre and because the movement will be 0, after reaching the top dead centre and then it reverses direction.

So, the distance travelled by the piston from the top dead centre to bottom dead centre or from bottom dead centre to top dead centre is called stroke, generally given by the symbol L. So, the stroke is just the physical distance between these two dead centres. And one stroke movement of the piston refers to the movement from one dead centre to the other dead centre. So, L refers to the stroke and let us say D refers to the bore; bore is nothing but the diameter of the cylinder.

Or if we are talking about a cylinder with noncircular cross section, then the average or hydraulic diameter of the cylinder. This bore to stroke ratio that is D/L is one of the important design criteria for reciprocating engines. Then, you can see when the piston reaches the top dead centre i.e., piston is something like this then, you can see there is a small portion left on top of this, which is void, the piston is not allowed to go into this. This particular portion is thus the clearance volume, this is given such name because here the objective is to allow certain clearance, so that the piston is not able to hit the top of the cylinder or the head of the cylinder. And the volume swept by the cylinder as it travels from one dead centre to other dead centre that is called the swept volume or displacement volume. So V_c is the clearance volume, which is again a design level criterion because of the design level itself, we can specify how much distance the piston is going to travel. Then we have a stroke volume (V_s) or displacement volume, sometimes also even called swept volume, there are so many names of the same thing.

Now, how much will be the magnitude of this stroke or displacement volume? This, you have to remember this corresponds to the change in the volume of the system as it moves from one dead centre to the other dead centre.

So, movement from one dead centre to other dead centre refers to the movement of the circular piston by a distance *L*, so it has to be the cross-section area of the channel. The stroke or displacement volume:

$$V_s = \frac{\pi}{4} D^2 L$$

then, the total volume; total volume (V_t) of the cylinder refers to the volume covering from bottom dead centre till the head of this, so total volume is the total volume of the cylinder available when the piston is at the bottom dead centre. So, total volume has to be a summation of the clearance volume and the stroke volume.

$$V_t = V_c + V_s$$

Now, if you look back at the diagram, there are several things that have been mounted on the head of the cylinder. This is a spark plug or fuel injector, when we are talking about SI engines or gasoline engines that generally have a spark plug, whereas we will talking about a diesel engine that generally has a fluid injector. So, the spark plug we can find in case of SI engines. In SI engine we have the spark plug, whereas CI engine we have a fuel injector and the ratio of this total volume to the clearance volume is called; generally, it is denoted by symbol *r,* it is called compression ratio.

$$r = \frac{V_t}{V_c}$$

Compression ratio is the single most important parameter for any reciprocating engine. Of course, there are several parameters which influences the performance of a reciprocating engine. But the compression ratio generally given by the *r* is the most influential one and while characterising the ideal cycles. We shall be discussing about the effect of this compression ratio. So, these are the brief things to know about the reciprocating engines. We know that there is a piston which keeps on moving up and down from one dead centre to other dead centre and depending upon whether we are having a spark plug or a fuel injector, we can have two kinds of engine.

One is SI engine which is having the spark plug, other is CI engine which is a fuel injector. SI engines are engines which run on some gasoline group of fuel like petrol or LPG or CNG. Whereas, the fuel injector is associated CI engine which run on diesel engines i.e., they use diesel as the fuel. Also if you can see on the; go back to the figure on either side of the spark plug, we have two valves; one of the valve is called the inlet valve through which fluid is allowed to enter the engine, other is the exhaust valve through which the exhaust gas is allowed to go out. If you look carefully now, the crank mechanism is actually having a rotary motion of the crankshaft and the piston is having the reciprocating motion. So, the crank mechanism is actually is allowing the conversion of this rotary motion to reciprocating motion or vice versa. And now, when the piston moves from say the bottom dead centre to the top dead centre, i.e., moving upward direction from bottom dead centre to the top dead centre, the crankshaft is having one half revolution or 180^0 revolution. That means,

$$1 \text{ stroke of the piston} \equiv 180^0 \text{ rotation of crankshaft}$$

So,

$$2 \text{ strokes of piston} \equiv 360^0 \text{ rotation of the crankshaft or one complete revolution}$$

And accordingly, how much strokes of the piston or how much revolution of the crankshaft we need to compete one cycle? We can have 2 kinds of cycle:

1. 4-stroke cycle: A 4-stroke cycle involves four strokes of the piston or two full revolution, I should say, 4×180^0 rotation of the crankshaft.
2. 2-stroke cycle: A 2-stroke cycle is completed just in two strokes so, we can have just one revolution of the crankshaft to complete the cycle.

So, these are two common classifications of engines but we are not going to talk anything about 4-stroke and 2-stroke cycles as of now, but we shall be talking about SI and CI engines mostly in conjunction with this difference of spark plug and fuel injector.

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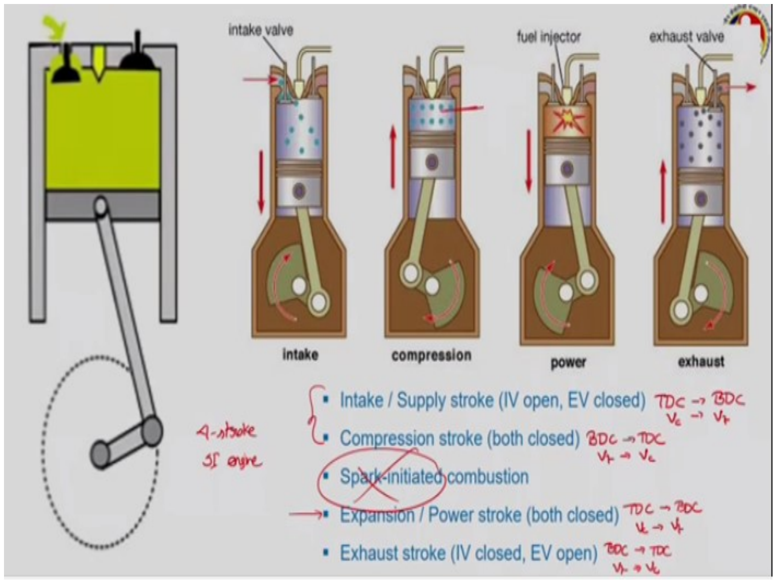

Now, let us see how a reciprocating engine works. Here I have a small animation taking from YouTube. Just look at this, this is the piston then, this is your inlet valve through which the fuel will be allowed to come in, this the exhaust valve through which the exhaust gas will be going out, this is your spark plug. So, initially when the piston is at the top dead centre somewhere here, both the valves are closed.

Then as the piston starts to go down like shown in this diagram, the inlet valve opens, observe that the inlet valve is open but the exhaust valve remains closed here. And a mixture of fuel and air is allowed to come in, so as the mixture of fuel and air is coming in, the piston continues to go down there we making space for this mixture to come in. And this particular movement or action continues till the piston which is at the bottom dead centre.

So, this particular thing is called intake or supply stroke during which the IV that is inlet volume is open, EV or exhaust valve remains closed. So at the beginning of the inlet stroke, the piston is at the top dead centre, at the end of it, it is at the bottom dead centre. Now, as the piston reaches the bottom dead centre, both the valves remains closed i.e., inlet valve closes, exhaust valve wad already closed.

Now, the piston starts to go up, as the piston is going up both the valves were closed. So, the volume of the gas mixture that has been supplied during the inlet stroke or intake stroke that is reducing and therefore and the space will be increasing thereby allowing the compression of the gases. So, this is called the compression stroke during both the valves are closed and piston is moving from bottom dead centre to top dead centre.

So, during the inlet stroke, piston is moving from top dead centre to bottom dead centre, so that the volume of the gas mixture at the top dead centre, volume is the clearance volume, it is changing to the total volume during this. During the compression stroke, piston is moving from bottom dead centre back to top dead centre, there is a change in volume from total volume back to the clearance volume, so there is a large change in the volume.

And depending upon the ratio of these two, there will be significant change in the pressure of this. So, when the compression stroke increases, the piston will be somewhere here at the top dead centre and then there is a very small volume left which is nothing but the clearance volume and a very high-pressure gas that is stored there. In fact, the temperature of the gas will also keep on increasing during the compression stroke, so you have a very high pressure and high temperature gas stored in this clearance volume at the end of the compression stroke.

Then at the end of the compression stroke, the spark plug becomes active. The spark plug with the help of the associated circuitry and the battery of the vehicle produces one spark. Because of the spark as the gas mixtures has already at a high pressure and temperature immediately, combustion reaction starts. And this combustion is almost instantaneous i.e., almost instantaneously before the piston starts to go back towards the bottom dead centre, the combustion is virtually complete thereby releasing a huge amount of energy.

And as a large amount of energy is released, the temperature of this gas mixture increases rapidly and here actually, we are talking about in increase in the order of 1000 K or even higher, just within a fraction of seconds. And because of such large increase in the temperature, the gas will try to expand and as it is trying to expand now, it will force the piston to go down there by initiating this expansion or power stroke.

During the expansion, power stroke again both the valves remains closed, piston is moving from top dead centre to bottom dead centre, thereby facilitating change in volume from clearance volume to total volume. But one difference with the expansion stroke to the earlier two strokes is that in the previous two cases, the piston is the one which is forcing the gas to move. Whereas, in this case, in the expansion of power stroke, it is the gas which is making the piston to move, thereby, transferring power to the crankshaft through the crank mechanism.

And then the crankshaft can be connected to the vehicle, where the power is transmitted and therefore, we can have an external power. Finally, when the piston reaches the bottom dead centre, it is expanded to the fullest thereby losing almost all its potential to deliver work. So, as the piston because of its inertia, piston continues to move, because during the power stroke, the piston has given sufficient amount of energy to the flywheel in the connected to the crankshaft.

And because of that inertia, the flywheel continuous to rotate thereby making the piston to move up again towards the top dead centre. And now, at the end of the power stroke, the entire total volume is filled up with a burn gases so, you have to get rid of this gases and therefore, the exhaust stroke is initiated during the exhaust valve opens and the gases are moved out or forced out, which is called the exhaust stroke.

During the exhaust stroke, the inlet valve is closed but the exhaust valve is open, piston is moving from bottom dead centre towards the top dead centre, causing change in volume from the total volume to the clearance volume. So, these are the four strokes and what I have just shown here that is actually a 4-stroke SI engine. If we are talking about a CI engine, then strokes remain the same, there are two major differences. During the inlet stroke, it is not a mixture rather only air is supplied, it is only air which is supplied during the inlet of supply stroke, the air is compressed to high pressure and temperature during the compression stroke. Then instead of having a spark-initiated combustion, there is a fuel injector, during each fuel is injected into this high temperature and pressure air environment. Because of the presence of high temperature, this will immediately start combustion leading to a self-ignition-initiated combustion. So, in SI engine, the combustion is spark initiated, whereas CI engine it is self-ignited, rest of the processes remain the same.

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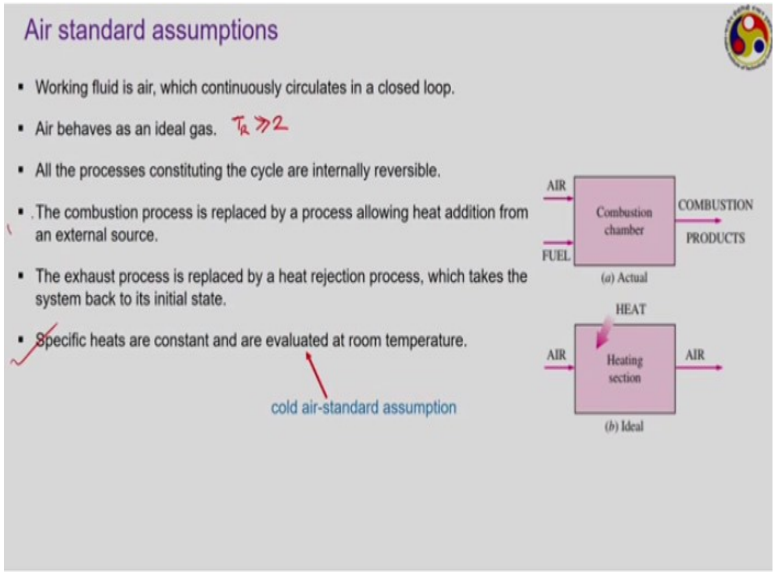

So, we have to now devise one ideal cycle to simulate this particular thing. And as you can see because of the presence of this combustion processes etc., they are extremely complicated to theoretical analyse and even if we go for idealisation, we cannot go for a Carnot cycle because they are workings are very much different compared to Carnot cycle. So we shall be deriving or conceptualising two other ideal cycles today.

One corresponding to SI engine, other corresponding to the CI engine. But before that we has to assume a few things and these assumptions are known as air standard assumptions.

1. The first assumption is the working fluid is air which is continuously circulated in a closed loop that is we are actually getting rid of the inlet and exhaust processes, we are assuming that it is a closed cycle, a fixed mass of air is trapped inside the cylinder, when the piston is moving up and down, it is the temperature and pressure of the air that keeps on changing, but there is no inflow and outflow, or there is no intake stroke or exhaust stroke.
2. Air is assumed to be as an ideal gas, which is not a bad assumption because the levels of temperatures at which generally, the air standard cycles operate, you will invariantly feel that their reduced temperature is will above 2, i.e.,

$$T_R >> 2$$

which is a good condition to apply the ideal gas assumption.

3. All the processes constituting the cycles are internally reversible as you have mention but not necessarily externally reversible, so internally reversible is low friction present there.
4. Then the combustion process is replaced by a process allowing heat addition from an external source. Combustion is a highly irreversible process and therefore in ideal cycle, we assume that there is no combustion. That is an actual cycle, we have air and fuel coming in, there is a spark which is initiated in the SI engine and combustion products at high pressure and temperature are at least at high temperature that goes off. But here we are assuming that it is air which is coming to a heating section, heat is being supplied to some external source, it is only air going out again, with that same high-pressure temperature limit. So, you are getting rid of the combustion and replacing that by a heat addition process.
5. Similarly, the exhaust process also replaced by a heat reaction process which takes the system back to the initial state. So, there is no exhaust process. It is only be a heat reaction process to get the system back to the initial condition.
6. Specific heats are constants, that is an important assumption because in air standard cycle, we have to consider will large change in temperatures and correspondingly, large changes in the specific heats. But to simplify the analysis, we assume specific heat to be constant and they are evaluated at room temperature. As we are taking the heat values, specific heat values are at room temperature, these also sometimes called the cold air standard assumptions. Now, this particular one is the biggest source of inaccuracies in the efficiency prediction of ideal cycle, because specific heats are always a strong function of temperature. Another big source of irreversibilites is a presence of the combustion.

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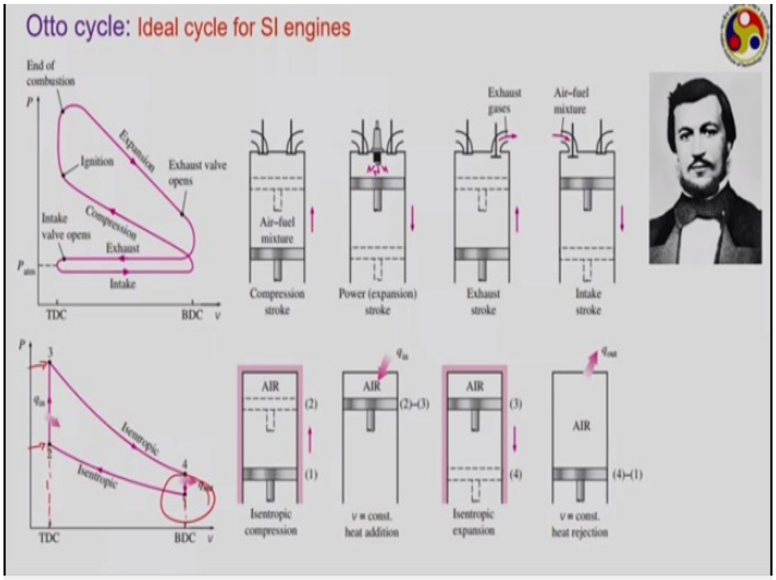

So, the cycle that we have to consider here is called the Otto cycle which is the ideal cycle for SI engine, conceptualised first by Nicholas Otto, the Frenchman. See, this is the ideal scenario or I should say the actual scenario. We have a compression stroke then, power stroke, exhaust stroke and intake stroke, going on in cycle and also between compression power stroke, we have the combustion process by spark.

If we first plot the compression stroke then during the compression stroke, the piston starts from the bottom dead centre, this is the bottom dead centre, let me draw a vertical line to signify the bottom dead centre. So, this is your bottom dead centre, this is the top dead centre. So, the piston is here at the beginning of compression stroke, being the compression stroke as the piston moves up, the gas is being compressed and accordingly, it is volume reduces pressure increases. When it is very close to top dead centre somewhere here, the ignition is initiated by the spark, because of which you can see there is hardly any change in the volume, because the piston is virtually reach the top dead centre, but there is a rapid change in pressure. So, during the combustion process, this much change in pressure takes place, is a very rapid process hardly any change in volume almost instantaneously, the combustion is done.

So, system pressure and simultaneously, temperature increase to very high value. Then, we have the expansion stroke, this high pressure-temperature gas is expand starting from this particular point to the point whether exhaust valve opens. So, this is the exhaust stroke, the exhaust valve theoretically should open after attaining the bottom dead centre position. But practically, to take care of the inertia of the exhaust valve etc., it is open slightly before the piston reaching the bottom dead centre, so you have the exhaust process.

So, during the exhaust process, the exhaust gases go out to get the system back to the atmospheric pressure and then we open the inlet valve to have the intake process to get again the fresh mixture of fuel and air to come inside the cylinder. So, this is the actual cycle. Then, how we can idealise this using the air standard assumptions? Here it is, we have an isentropic compression process, it is compression, it is adiabatic and also internally reversible that is why it is isentropic.

So, the compression process is plotted here by the process 1 to 2, the isentropic compression starting from bottom dead centre to the top dead centre. This is your bottom dead centre location, this is the top dead centre location, piston starts from this particular point and finishes here during the compression process. Then, we have the constant pressure, constant volume heat addition process. Piston is stopped at the top dead centre position; heat is being supplied from the external source thereby causing a change in both temperature and pressure.

So, 2 to 3 that is from this point heat addition starts and finishes at point number 3, volume remains constant at TDC. Then the isentropic expansion starting from 0.3 to 0.4, during this expansion process, there is no heat transfer involved, process is assumed to be internally reversible, so it is isentropic expansion. And then we have a constant volume heat rejection process. During this constant volume heat rejection process, the volume retained to be at BDC and heat is being allowed to flow out of the system, thereby allowing it to come back to this initial point which is point number 1. So, this is the ideal cycle for an SI engine which is called the Otto cycle.

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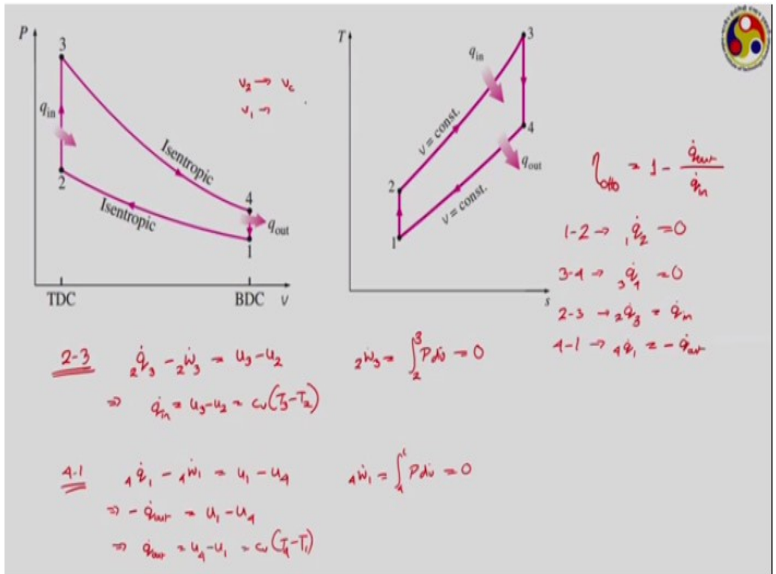

The same *Pv* diagram shown here, so we can see there are four processes: two isentropic processes and two constant volume processes. The same thing shown on a *Ts* diagram 1 to 2 isentropic processes, entropy is constant is the vertical line, same applies to 3 to 4. But during 1 to 2, temperature increases during 3 to 4 temperature decreases and 2 to 3 and 4 to 1 are constant volume processes.

So, if we want to analyse each of these processes quickly then, as we know the efficiency of this Otto cycle is going to be as we wrote earlier:

$$\eta_{Otto} = 1 - \frac{\dot{q}_{out}}{\dot{q}_{in}}$$

a q notation we are using to denote heat transfer per unit mass. So, you have to estimate the total heat transfer associated with the process. Now, look at the processes: process 1 to 2, how much heat transfer is involved in that? It is an isentropic process.

$${}_1\dot{q}_2 = 0$$

Process 3 to 4,

$${}_3\dot{q}_4 = 0$$

again, that is 0 because that is an isentropic process.

Process 2 to 3,

$${}_2\dot{q}_3 = \dot{q}_{in}$$

which is the heat being supplied to the system.

Similarly, process 4 to 1,

$$_4\dot{q}_1 = -\dot{q}_{out}$$

during which the heat is being rejected to the surrounding.

So, there are only two heat transfers involved in the system. Then you have to estimate these twoheat transfers by analysing process 2 to 3 and process 4 to 1.

So, let us first analyse 2 to 3. During process, 2 to 3 if we apply the first law of thermodynamics,

$$_2\dot{q}_3 - \quad _2\dot{w}_3 = u_3 - u_2$$

here we are directly applying the condition that changes in kinetic and potential energies are neglected and therefore, the changes in total energy of the system reduces only to the internal energy. Now, process 2 to 3 is a constant volume process, so,

$$_2\dot{w}_3 = \int_2^3 Pd\dot{v} = 0$$

as there is no change in volume so, this is = 0. That means,

$$_2\dot{q}_3 = u_3 - u_2$$

and we have assumed air to be an ideal gas. And for an ideal gas, we know the change in specific internal energy can be written as:

$$= c_v(T_3 - T_2)$$

if you are confused, you can refer to module number 2, where we have proof that for where we have developed expression for du and if you put the ideal gas equation of state there, you can prove that the du reduces to simply c_vdT.

Similarly, for process 4 to 1,

$$_4\dot{q}_1 - \quad _4\dot{w}_1 = u_4 - u_1$$

Now as per our notation,

$$_2\dot{q}_3 = \dot{q}_{in}$$

Similarly,

$$_4\dot{q}_1 = -\dot{q}_{out}$$

Now,

$$ {}_4\dot{w}_1 = \int_2^3 Pd\dot{v} = 0 $$

again, there is no change in specific volume during this process as it is being done maintaining the piston at bottom dead centre, so this also equal 0. So, this becomes nothing but $u_4 - u_1$. i.e.,

$$ -\dot{q}_{out} = u_4 - u_1 $$

or we can write:

$$ \dot{q}_{out} = u_1 - u_4 = c_v(T_1 - T_4) $$

assuming to be an ideal gas and also assuming c_v to be constant.

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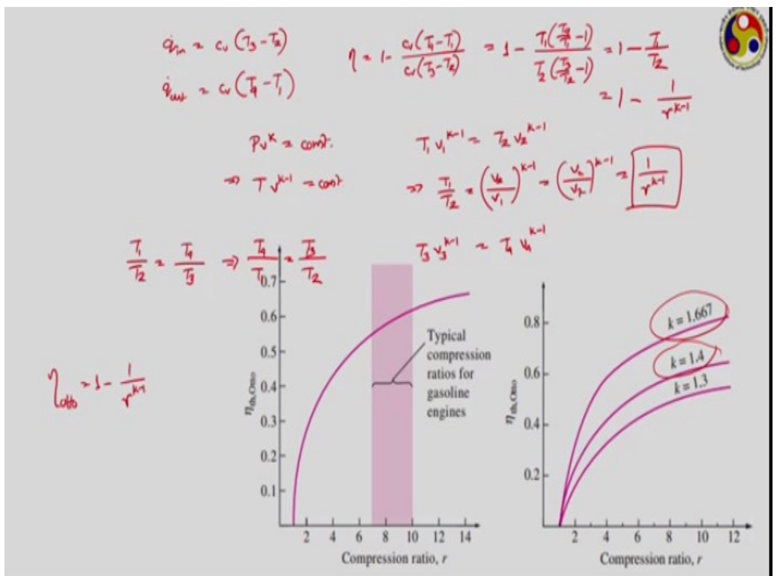

So, we have now got,

$$ \dot{q}_{in} = c_v(T_3 - T_2) $$

$$ \dot{q}_{out} = c_v(T_1 - T_4) $$

this is what we have developed here so, if we combine them to determine the efficiency, it is:

$$ \eta = 1 - \frac{c_v(T_3 - T_2)}{c_v(T_1 - T_4)} $$

Here I made an error actually while writing because we have $q_{dot\ out}$ in the numerator, so we have $T_1 - T_4$ in the denominator, we have $q_{dot\ in}$ correct so, $T_3 - T_2$, let me erase this and correct the above expression as:

$$ \eta = 1 - \frac{c_v(T_1 - T_4)}{c_v(T_3 - T_2)} $$

From the numerator, I am taking T_1 constant, so it is:

Actually, I made a mistake in the previous slide, look at this here the process 4 to 1 is happening from point 4 to 1. So, this has to be:

$$ {}_4\dot{q}_1 - {}_4\dot{w}_1 = u_1 - u_4 $$

So, accordingly all this will change, it is:

$$ -\dot{q}_{out} = u_1 - u_4 $$

and this will become now:

$$ \dot{q}_{out} = u_4 - u_1 = c_v(T_4 - T_1) $$

as trying to go quickly and that is why I made this mistake. So, this becomes:

$$ \dot{q}_{out} = c_v(T_4 - T_1) $$

so, we have to change it again here, it is:

$$ \eta = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)} $$

So, once we take T_1 common from numerator and T_2 common from denominator of second term, we have:

$$ = 1 - \frac{T_1\left({T_4}/{T_1} - 1\right)}{T_2\left({T_3}/{T_2} - 1\right)} $$

Now, for an ideal gas undergoing an isentropic process, we know that the process equation is

$$ Pv^k = constant $$

where

k is the ratio of specific heat

The above expression can also be written as:

$$ Tv^{k-1} = constant $$

by using the ideal gas equation of state. Therefore, for process 1 to 2 which is the first isentropic process, we can write:

$$ T_1 v_1^{k-1} = T_2 v_2^{k-1} $$

i.e.,

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1}$$

Now what is v_2 and what is your v_1? Just look at the diagram carefully, v_2 refers to the volume at the top dead centre, v_1 refers to the volume at the bottom dead centre. So, your v_2 is nothing but the reference to the clearance volume, v_1 is nothing but the reference to the total volume. So, it is nothing but:

$$= \left(\frac{v_c}{v_t}\right)^{k-1} = \frac{1}{r^{k-1}}$$

But before going any further, we have to analyse the other isentropic process which is 3 to 4. So, look at the process 3 to 4 for which we can write:

$$T_3 v_3^{k-1} = T_4 v_4^{k-1}$$

and if we write say:

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{k-1}$$

Now, again referring back to the diagram the 4 to 1 and 2 to 3 are constant volume processes, therefore v_4 and v_1 are equal, so if we replace here and v_3 is replaced with v_2, we can write:

$$= \left(\frac{v_1}{v_2}\right)^{k-1}$$

i.e.,

$$\frac{T_4}{T_3} = \frac{1}{r^{k-1}}$$

So,

$$\frac{T_1}{T_2} = \frac{T_4}{T_3}$$

or if we reorient them, we can write

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

Now, look at the expression for the efficiency:

$$\eta = 1 - \frac{T_1\left({T_4}/{T_1} - 1\right)}{T_2\left({T_3}/{T_2} - 1\right)}$$

So, how can we simplify this? As

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

We can simplify efficiency as:

$$\eta = 1 - \frac{T_1}{T_2}$$

and then using this compression ratio relation, it becomes:

$$\eta = 1 - \frac{1}{r^{k-1}}$$

So, the efficiency for Otto cycle is nothing but a simple function of the compression ratio and the ratio of specific heat:

$$\eta_{Otto} = 1 - \frac{1}{r^{k-1}}$$

Here I have got a diagram, let me erase it again to write separately so, I hope you have already noted down that is why I am clearing the text from here to make the diagram clear. Here, we have plotted the efficiency as a function of the compression ratio. As the compression ratio increases, the efficiency keeps on increasing rapidly. Of course, the slope keeps on reducing as the compression ratio keeps on increasing, but it is always logical to have higher compression ratio as that is going to give you higher value of this efficiency.

Similarly, what about the effect of *k*? As *k* remains smaller, the efficiency will be higher for the same compression ratio. So, if you are using a monoatomic gas for which *k* is around 1.67 then, it is going to give you higher efficiency compared to an engine working on a diatomic gas for which *k* is about 1.4. So, engine working with helium is always going to give you higher efficiency compared to an engine working with air.

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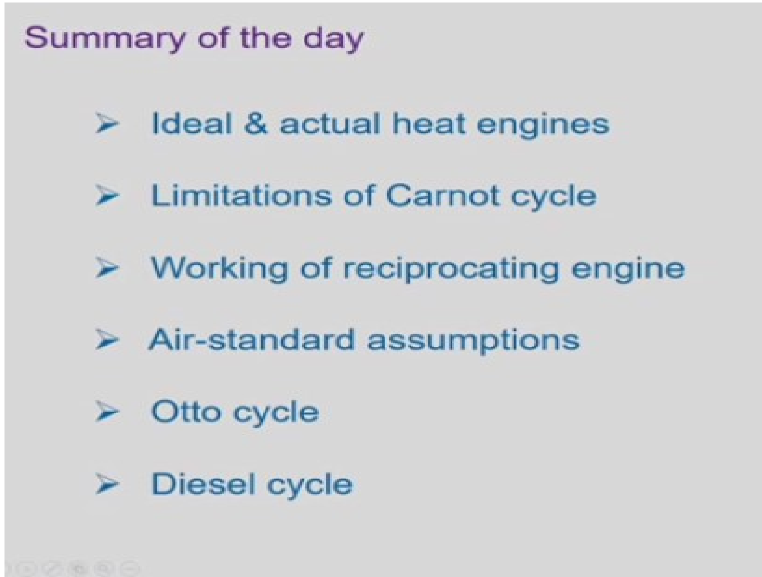

So, this is the way we can analyse a simple Otto cycle. That takes us to the end of today's discussion, I would like to discuss any further on the Otto cycle, the practical aspects of that in the next one because I have run out of the time today. Just to summarise we have discussed about ideal and actual heat engines, then we talked about the limitations of Carnot cycle from practical point of view, discuss the working of reciprocating engine.

Unfortunately, that animation did not work. But I hope the working principle is clear for a 4-stroke SI engine, then we discussed the air standard assumptions and we talked about the Otto cycle. I was thinking about discussing diesel cycle today, but I was not able to cover. But that is fine because in the next lecture, I can spend some more time on Otto cycle, then, moving on to the diesel cycle. Till then you revise this lecture try to develop the expression for the Otto cycle on your own.

And in the next one, we can go on the discussion of the diesel cycle, Thank you.