Basics of Mechanical Engineering-3

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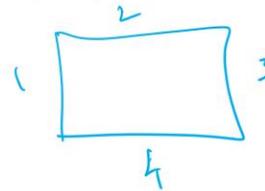
Indian Institute of Technology, Kanpur

Week 03

Lecture 14: Gas Cycles in Thermodynamics Part 2 of 2

Welcome to the second part of the Gas Cycle in Thermodynamics. In the first lecture, we saw what the Air Standard Cycle is, then we saw the Otto Cycle.

Now, we will see the Diesel Cycle. So friends, you would have enjoyed traveling by a diesel car, bus, or train. So diesel trains also exist. So the Diesel Cycle is one of the most popular cycles. When we go back, it finally boils down to the PV diagram and TS diagram. The Diesel Cycle consists of two isentropic reversible adiabatic processes. One isobaric reversible constant-pressure process and one isochoric reversible constant-

volume process. So there are four processes because if you have a box, there are four processes: 1, 2, 3, and 4. So it is said that two of them are isentropic in nature. What is isentropic, and it is also a reversible process. Reversible adiabatic. It is very important. Adiabatic is also very important. We have seen what is adiabatic. Reversible cycle also we have seen. Then one is isobaric. So it is again reversible constant pressure because bar pressure. Then one is isochronic.

So, which is constant volume and all the processes are reversible. The cycle was proposed first by Rudolf Diesel in 1890. So, he proposed a cycle. Then subsequently, lot of technologies were developed and then these two got merged. The diesel cycle is the ideal cycle for compression ignition engines. We call it as CI. Petrol is called as SI, spark ignition. This is compression ignition. So it clearly says compression, compress and then it ignites. Unlike spark engine, combustion in diesel is initiated by the high temperature of compressed air into which the fuel is injected.

This results in high thermal efficiency. The cycle led to the development of technology. You can see there will be a big difference in the engine design itself. So here in diesel, you will have an inlet valve and an outlet valve, which are controlled separately. But whereas, when you go to petrol, it is done in the inlet fold, and then the outlet fold is on one side. So there is high thermal efficiency. So why is the thermal efficiency high? Here it is compressed and ignites. There it is trying to compress, and then there is a spark which tries to ignite. So when the exhaust happens, maybe there is a possibility of rich fuel getting removed without burning.

It is possible in petrol, but in diesel, it is reduced to a large extent, especially at part load conditions, making the diesel engine widely used in heavy-duty vehicles, marine applications, and power generation. You can also use the Diesel Cycle in power generation, which is nothing but DGs, diesel generators.

Diesel Cycle

P-V DIAGRAM
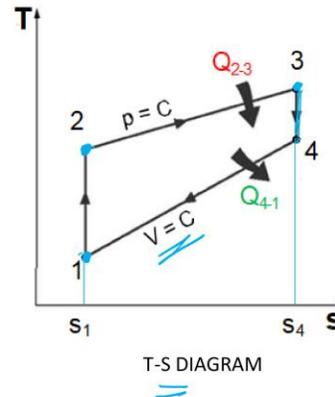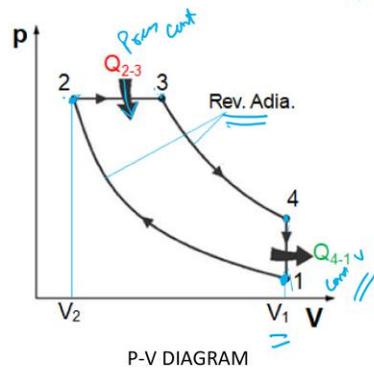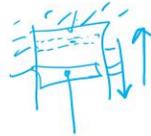
T-S DIAGRAM

As I told you, the PV diagram—we are going to look into the PV diagram and the TS diagram: pressure-volume diagram, temperature-entropy diagram. So the cycle starts from 1 here; the volume is 1, and then the volume is compressed. If you go back and want to visualize, you have a cylinder and then a piston.

So the volume is reduced from V1 to V2. Once it is reaching the highest value, so then there is a Q which is introduced. And we make sure the pressure is constant. So now the piston is at its maximum position. The piston is at maximum position.

Then after it has reached its maximum position and when the Q is injected, the Q which is there, the heat, whichever is there, so it is trying to ignite and afterwards it will try to move down. When it is trying to move down, then the pressure will be reduced, the volume is expanded, which is from 3 to 4. The process 1 to 2 and 3 to 4 follows reversible adiabatic process. 2 to 3, it is a constant pressure process. Once it has reached the lowest value or the stroke end of the piston, then from 4, it tries to go to 1.

So, at this point, it is constant volume process. So 2, 3 is constant pressure process which is reversible. 4, 1 is again a constant volume process which is reversible. This is what we have said here. It has two isoentropic reversible adiabatic which happens between 1 to 2 and 3 to 4.

And then isobaric, which is constant pressure from 2 to 3. And we said constant volume is between 4 and 1. So between 4 and 1, the heat is extracted. So when I draw the

corresponding TS diagram for the same, you can see temperature versus entropy. The process starts from 1.

When there is compression happening, the temperature increases to 2. Why? Because the volume is compressed. When the volume is compressed, there is naturally a temperature increase. Then afterward, what happens is, from 2 to 3, where you are trying to put an input Q, there is a constant pressure process, and during this time the entropy increases from 2 to 3.

The entropy increases. Then, from 3 to 4, when there is expansion happening, the entropy remains constant. And from 4 to 1, once there is a constant volume, the entropy reduces from 4 to 1. When this happens, you see constant pressure and constant volume. So isentropic compression happens from 1 to 2. In this step, the piston moves upward, as I told you before. Compressing the air-fuel mixture inside the cylinder.

Diesel Cycle

- **Isentropic Compression (1–2):**

  In this step, the piston moves upward, compressing the air-fuel mixture inside the cylinder. The compression happens **rapidly and without heat exchange** (adiabatic), so the temperature and pressure of the gas increase significantly. This process stores energy in the form of increased internal energy. (u)

- **Constant Volume Heat Addition (2–3):**

  At the end of compression, a spark ignites the fuel-air mixture. **Combustion occurs quickly**, and heat is added at **constant volume** because the piston is momentarily at the top dead center. This sudden addition of energy causes the pressure and temperature of the gas to rise sharply.

The compression happens rapidly without heat exchange. That is why it is called adiabatic. Constant temperature. So, the compression happens rapidly and without heat exchange to the atmosphere, which is why it is called adiabatic. So, the temperature and the pressure of the gas increase significantly. Temperature increases, and pressure increases. This process stores energy in the form of increased internal energy, which we

have already seen as U. Now, let us go to the next step, 2, 3. Please note down the PV diagram 2, 3 and the TS diagram 2, 3.

It is called the constant-volume heat addition process. Q is getting added. At the end of compression, ignition happens in the air-fuel mixture. The combustion occurs quickly, and the heat is added at constant volume. So, if you see here, the volume is constant because the piston is momentarily at the top dead center. This sudden addition of energy causes the pressure and temperature of the gas to rise.
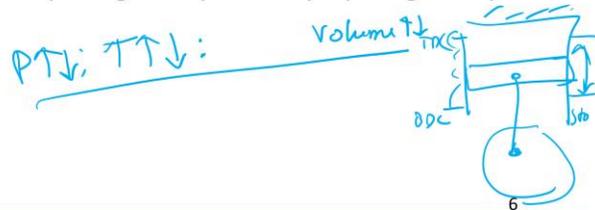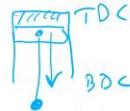

The next one is the isentropic process, which is otherwise called a power stroke. It happens between 3 and 4. The pressurized gas now pushes the piston down because there is a closed area. The piston is at its topmost position, and here the ignition has happened.

So now, there is a lot of temperature. The pressures are very high. So what is left is, this fellow has to come down. The piston has to come down. So the high-pressure gas now pushes the piston down, doing useful work on the crankshaft.

So now this happens. The other end is attached to a crankshaft, and that in turn is attached to an engine. So, crankshaft. This expansion occurs without any heat exchange. That is why it is called adiabatic.

Without any heat exchange, it is called adiabatic. As the gas expands, its temperature and pressure fall. This is called the power stroke because it is moving down. The other end of the piston is attached to the crankshaft. Now, the crankshaft rotates.

Once it rotates, it is further attached to the engine. The last step is constant volume heat rejection 4-1. Where is it? 4-1, 4-1, PV diagram 4-1, TS diagram 4-1. It is constant volume heat rejection.

Once the piston reaches the bottom dead center (this is TDC, and this is BDC), the exhaust valve opens at the top, and the gas is cooled at constant volume, rejecting heat to the surroundings. That is what happens in the exhaust. When you drive a bike or a diesel car, or operate an engine, you will always have exhaust coming out, right? That is nothing but once the piston reaches the bottom dead center, the exhaust valve opens, and the gas is cooled at constant volume, rejecting heat to the surroundings. This reduces the pressure and temperature of the gas, completing the cycle and preparing the system for the next cycle. So, friends, we are just playing around: P increases, T increases, P decreases, T decreases, all at constant volume. And this is done by a piston-cylinder assembly. And this fellow rotates. Okay. So here, you attach it to the gear. So this rotates. This moves up and down.

This is the stroke. This is TDC, and this is BDC. This is what that is, friends—the Diesel Cycle. So, if you understand this diagram, the only thing you have to understand is: pressure increases, pressure decreases, temperature increases, temperature decreases. The volume can be constant, or the volume can also increase or decrease.So, these are the three parameters you play with, and this is done in a cycle. When you call it a cycle, it starts and ends at the same point. So, that is why it is called a cycle.

Diesel Cycle
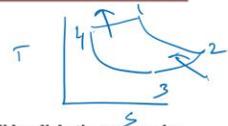
Heat supplied: $Q_{sup} = Q_{2-3} = mC_p(T_3 - T_2)$

Recalling that;

For process 1-2: Isentropic or reversible adiabatic compression

Heat rejected: $Q_{rej} = Q_{4-1} = mC_v(T_4 - T_1)$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r_c^{\gamma-1} \Rightarrow \frac{T_2}{T_1} = r_c^{\gamma-1}$$

$$\eta = 1 - \frac{Q_{rej}}{Q_{sup}} = 1 - \frac{mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} = 1 - \frac{1(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

For process 2-3: Isobaric or constant pressure heat supply

$$\Rightarrow \eta = 1 - \frac{T_1[(T_4/T_1) - 1]}{\gamma T_2[(T_3/T_2) - 1]}$$

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \Rightarrow \frac{T_3}{T_2} = \frac{V_3}{V_2} = \rho \Rightarrow \frac{T_3}{T_2} = \rho$$

Let's define the volume ratios:

For process 3-4: Isentropic or reversible adiabatic expansion

Compression ratio: $r_c = \dfrac{V_1}{V_2}$

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)_{=V_1}^{\gamma-1} = \left(\frac{V_3/V_2}{V_1/V_2}\right)^{\gamma-1} = \left(\frac{\rho}{r_c}\right)^{\gamma-1}$$

On substitution into Eqn. (3);

$$\Rightarrow \eta_{Diesel} = 1 - \frac{[\rho^\gamma - 1]}{\gamma\, r_c^{\gamma-1}[\rho - 1]}$$

Expansion ratio: $r_e = \dfrac{V_4}{V_3}$

$$\Rightarrow \frac{T_4}{T_1 r_c^{\gamma-1}\rho} = \left(\frac{\rho}{r_c}\right)^{\gamma-1} ; \Rightarrow \frac{T_4}{T_1} = \rho^\gamma$$

$$\therefore \eta_{Diesel} = 1 - \frac{1}{r_c^{\gamma-1}}\left[\frac{\rho^\gamma - 1}{\gamma(\rho - 1)}\right]$$

Cut-off ratio: $\rho = \dfrac{V_3}{V_2}$

$$\Rightarrow r_c = r_e\rho$$

Now, continuing from there, the heat supplied (Q supply) is between 2 to 3. So, if you go, you can see a diagram like this.

Mean Effective Pressure (p_m or mep)

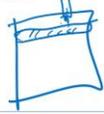$$p_m = \frac{p_1 r_c \left[\gamma r_c^{\gamma-1}(\rho-1)-(\rho^\gamma-1)\right]}{(\gamma-1)(r_c-1)}$$

So, the mean effective pressure Pm, which we saw last time also, or mep, is expressed as PM in this form. So, it is basically trying to play with all these parameters you try to juggle it and then get this form.

$$p_m = \frac{p_1 r_c \left[\gamma r_c^{\gamma-1}(\rho-1)-(\rho^\gamma-1)\right]}{(\gamma-1)(r_c-1)}$$

Difference between Actual Diesel and the Otto Engines:

Otto Engine	Diesel Engine
1. Homogenous mixture of fuel and air formed in the carburetor is supplied to engine cylinder.	1. No carburetor is used. Air alone is supplied to the engine cylinder. Fuel is injected directly into the engine cylinder at the end of compression stroke by means of a fuel injector. Fuel-air mixture is heterogeneous.
2. Ignition is initiated by means of an electric spark plug.	2. No spark plug is used. Compression ratio is high and the high temperature of air ignites fuel.
3. Power output is controlled by varying the mass of fuel-air mixture by means of a throttle valve in the carburetor.	3. No throttle value is used. Power output is controlled only by means of the mass of fuel injected by the fuel injector.

Now let us try to compare auto cycle and diesel cycle. Auto engine is homogeneous mixture of fuel and air formed in the carburetor is supplied to the engine cylinder. It is a homogeneous mixture of air fuel. So, that is why, we always talk about air fuel ratio, air fuel ratio formed in the carburetor.

So what is carburetor is a part where there is a mixing of fuel and air. Liquid comes from one side, petrol comes from one side, air is drawn inside through in front of carburetor. At the carburetor there is a mixing happening. So the fuel and air formed in the carburetor is supplied to the engine cylinder. Next, once it is supplied, then there is a ignition which is initiated by a spark plug. So, when you have compressed completely the cylinder, piston goes very close, when you have compressed,

Then there is a spark plug which tries to spark. Moment it tries to spark, there is a very small place where air fuel mixture is there and it is rich. So moment it is there, the spark ignites, then there is a reaction. Then this tries to push the piston down. So, that's what it says, ignition is initiated by means of a spark plug. So, in petrol engine, you will always have a spark plug. So, the power output is controlled by varying the mass of the fuel air mixture, so you can make it rich, you can make it lean.

So, the power output with what power it comes out is called as a power output is controlled by varying the mass of air fuel mixture by means of throttle valve in the carburetor. So, basically when you are trying to drive a car or a scooter, you try to

accelerate. When you accelerate, what you do is there is a cable which connects the accelerator to the carburetor. Moment you start accelerating, the cable starts pulling. So in the carburetor, there will be a valve which is opening to maximum.

And when you try to release it, it shuts down. So once it shuts down, the air fuel mixture is brought to almost lean state. This is what happens in the Otto Engine. When we talk about Diesel Engine, there is no carburetor. So here the air alone is supplied to the engine cylinder.

The fuel is injected directly into the engine cylinder at the end of the compression stroke by means of a fuel injector. The fuel air mixture is heterogeneous. Same, whatever we talked about here in diesel engine also, the compression comes to the the dead. If you have a cylinder, this is your top dead center. Till here, the piston will come, and here you will have your spark plug. So now, instead of spark plug is removed, the carburetor is removed, so there is a air which is directly getting supplied into the engine. The fuel is injected directly into the engine cylinder at the end of the compression stroke by means of a fuel injector.

So, if you see a fuel injector, it will be something like this. It will have a cone and it will have holes. Through these holes, you spray the diesel inside the cylinder. So, the cylinder at the end of the compression stroke uses a fuel injector. The air-fuel mixture is heterogeneous in state.

So here, we don't use a spark plug. The compression ratio is high, and the temperature of the air ignites the fuel. That's the difference. So here, we have a spark plug. In diesel, we don't have a spark plug.

So, no throttle valve is used. So here, you use a throttle valve in a scooter or in a car, as I said. Here, no throttle valve is used. The power output is controlled by the mass of the fuel injected by the fuel injector. So, the amount of fuel getting injected.

So, here's what happens: the throttle, or whatever I said about the accelerator, is directly connected to the fuel injector. So, it is a very interesting thing. If you see diesel, when you fill it up, it is at normal atmospheric pressure. It is a tank filled with diesel. Now, you have an engine on the other end.

This engine has to be injected with fuel. And what gets injected into the fuel isn't like a pipe pouring there. So, you have to increase the pressure, not the temperature. So, what do we do? From the tank, we move it toward a pump.

So, in the pump, you try to increase the pressure. So when you try to increase the pressure, you should increase it in such a way that what comes out of the injector is all in droplets. So, it's almost like having a pipe—when you press the pipe end while watering the garden, you'll see small droplets of water coming out. Or you put a sprinkler, and you see the water gets atomized. So, diesel also has to be atomized, and the atomized diesel is pushed into the cylinder through the injector.

So, that is what is happening here. So, now the amount of fuel to be injected is the mass of the fuel injector. Is that clear, friends?

So now, let us try to take a combination of the Otto Cycle and the Diesel Cycle, which is called a Dual Combustion Cycle. In early compression injection engines, the fuel was injected when the piston reached the top dead center, and thus combustion lasted well into the expansion stroke.

The air-standard Diesel Cycle thus does not simulate exactly the pressure-volume variation in an actual modern compression injection engine. So, in modern engines, the fuel is injected before the top dead center, about 15 degrees. So, where is this top dead center coming up? Because I cannot control the displacement inside the engine, but where I try to take the output of this and connect it to a crank. So now, I try to talk about

the angle and what it can do with respect to 0 to 15 degrees. So, the Dual Combustion Cycle is a closer approximation to the modern compression injection engine, in which some part of the heat is added to the air at constant volume and the remainder at constant pressure.

Look at it. How does it happen? So, you will have 1 to 2 as compression, then 2 to 3, you see there, there is a constant volume, but there is a pressure increase. From 3 to 4, there is an expansion, which is happening, 3 to 4. And then, from 4 to 5, there is a complete expansion. So, when we say 3 to 4, there is a constant pressure. This is what is dealt with in the last paragraph.

The Dual Combustion Cycle is a closer approximation to modern compression ignition engines. In which some part of the heat is added to the air at a constant volume. So this is the constant volume. Between 2 to 3, you inject heat. Then, again from 3 to 4, when the pressure is constant, you inject heat.

So, this is called the Dual Combustion Cycle. So, 4 to 5 is reverse adiabatic. 1 to 2 is also reverse adiabatic. This PV diagram clearly shows how a Dual Combustion Cycle works. Now, let us go to the TS diagram because, for us, entropy (S) is very important, right? So, the TS diagram. In this, what happens is from 1 to 2, when we move from 1 to 2, there is a reduction in volume, so compression happens.

During compression, the temperature is constant. From 1 to 2, the temperature is constant. So, S is also constant. For a fixed entropy, the TS diagram clearly shows what happens to the entropy with respect to temperature. So, from 1 to 2, there is an increase in temperature with constant entropy.

There is no change in the system. From 2 to 3, where I raised the pressure while keeping the volume constant, you can see the volume remains constant. From 2 to 3, what happens? The temperature increases. Pressure increases, temperature increases, and entropy increases. Then, from 3 to 4, where I maintained constant pressure, you can see again there is an increase in entropy and temperature.

From 4 to 1, it is nothing but an expansion cycle. From 4 to 1, you can see the entropy is constant. From 4 to 5, there is an expansion happening. So, from 4 to 5, when you look at a TS diagram, there is a decrease in temperature, and entropy is constant. So, then from 5 to 1, the volume is constant. So, from 5 to 1, the entropy reduces.

The entropy reduces from S2 to S1, and the temperature also reduces. So, this PV diagram and TS diagram clearly show the Dual Combustion Cycle advantage.

Dual Combustion Cycle

- **Isentropic Compression (1–2):**

  In the first step, the piston compresses the air (or air-fuel mixture) inside the cylinder **without any heat exchange**. Since the process is adiabatic and reversible (isentropic), the pressure and temperature of the air increase significantly. This prepares the gas for efficient combustion.

- **Constant Volume Heat Addition (2–3):**

  At the end of the compression stroke, a portion of the fuel is injected and combusted **very rapidly**, causing a **sudden rise in pressure and temperature** at constant volume. This step resembles the heat addition process in the Otto cycle.

So, isentropic compression is from 1 to 2, as we have already seen. From 1 to 2 is isentropic compression. So, in the first step, the piston compresses air inside a cylinder without any heat exchange.

Since the process is adiabatic and reversible, the pressure and temperature of the air increase significantly. This prepares the gas for effective combustion. When we go from 2 to 3, it is a constant-volume heat addition. At the end of the compression stroke, a portion of the fuel is injected, and combustion happens very rapidly, causing a sudden rise in pressure and temperature. So, from 1 to 2, pressure and temperature also increase.

So after heat is added, pressure and temperature increase at a constant volume. This step resembles the heat addition in the Otto Cycle.
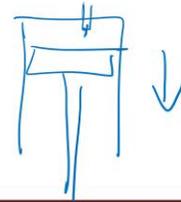
- **Constant Pressure Heat Addition (3–4):**

  Following the initial constant-volume combustion, the remaining fuel is injected and burns **more slowly**, while the piston begins to move down. This allows **heat to be added at constant pressure**, further increasing the temperature and volume of the gas. This phase is similar to the Diesel cycle's heat addition process.

- **Isentropic Expansion (Power Stroke) (4–5):**

  Now, the high-temperature, high-pressure gas expands **adiabatically** and does **useful work** by pushing the piston downward. As the gas expands, its pressure and temperature drop, and no heat is exchanged with the surroundings. This is the main **power-producing** stroke of the cycle.

Then, from 3 to 4, it is a constant-pressure heat addition, which we saw in the PV diagram at the top. So, following the initial constant-volume combustion, the remaining fuel is injected and burns more slowly while the piston begins to move down. At the top dead center, you have hit. Now, slowly, it will move down. So, following the initial constant-volume combustion, the remaining fuel is injected and burns more slowly.

That is injected, and it burns more slowly while the piston begins to move down. This allows the heat to be added at constant pressure. Further increasing the temperature and the volume of the gas. So, volume increases, and temperature increases. This phase is similar to the Diesel Cycle's heat addition process, which is there.

So that is why it is called the Dual Cycle. Now, 4 to 5 is an isentropic expansion. At very high temperature and pressure, the gas expands adiabatically and does useful work by pushing the piston down. As the gas expands, its pressure and temperature drop because, as the volume increases, the pressure reduces and the temperature also reduces. There is no heat exchange with the surroundings.

So, this means the power-producing stroke of the cycle is from state 4 to 5. Friends, now you will be able to enjoy and understand what an Otto Cycle is, what a Diesel Cycle is, and what a Dual Combustion Cycle is. All these things are very important because when you are in a car, a bus, or a diesel engine, you should now understand what happens

inside the machine. There should be some piston moving, a cylinder moving, some parts moving, some mechanical parts doing something. But what is the science behind it?

That comes from thermodynamics. So first, they studied thermodynamics. They understood the science. From there, they moved to technology. Today, they are working very hard to optimize the technology to achieve maximum efficiency.

And the efficiency, whatever we are calculating here, is ideal efficiency. So that means we will not consider whether there is a drop in temperature or what we measure T2 and T1; it can be static or dynamic. All these things happen. The volumes V1 and V2, whatever we measure, we assume there is no stray volume left. There is no stray air mixture left.

There is residual cleaning. And once we try to convert the science into technology, you will always try to have different valve opening and closing times. The height of the valve changes. The response time changes. So all these things are dynamic.

So we don't consider any of them. We don't consider the wear and tear. We don't consider the working fluid. So throughout, you see, where have we considered the working fluid? Say, for example, you have petrol or diesel, which is used in a high-speed car, a high-speed plane, a normal plane, or a normal car—whatever it is.

We do not compare the quality of the working fluid. We do not compare the specific heat it can produce, nothing. We do it only by science, and we try to assume all other things zero; we try to derive it. So, the efficiency, whatever we derive from here, is all theoretical efficiency. This theoretical efficiency will have almost a drop of 50%.

To actual efficiency. So, if you see the Diesel Cycle or Otto Cycle, what we study here, you will try to get efficiency of 40% or 50%. In some cases, academically or theoretically, you can get even 70%. In reality, it will be close to 25%. So, we saw 4 to 5; this is the power stroke.

Dual Combustion Cycle

- **Constant Volume Heat Rejection (5–1):**

  Finally, at the end of the expansion stroke, the gas is cooled at **constant volume**, rejecting heat to the environment.

  This brings the pressure and temperature down to the initial state, completing the cycle and preparing for the next compression.

P-V DIAGRAM   T-S DIAGRAM
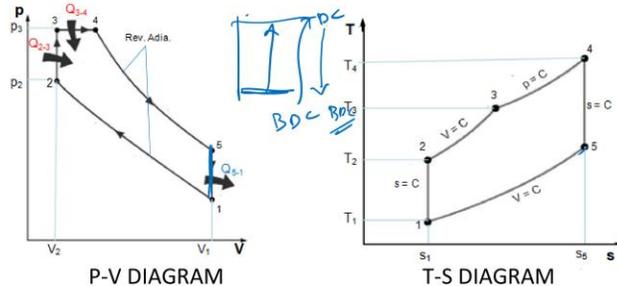
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Then, 5 to 1 is the heat rejection cycle. Whatever we have discussed till now, we have presented here. Finally, at the end of the expansion stroke, the gas is cooled at constant volume from 5 to 6. So, this is 5 to 1, and you can see the TS diagram 5 to 1; the delta S reduces, the T reduces. So, this brings the pressure and temperature down to the initial state, completing the cycle and preparing it for the next compression. So, what happens? Now you finished 1 to 2, 2 to 3, 3 to 4, 4 to 5. So, that means the piston moved from the bottom dead center to the top dead center and again from the top dead center to the bottom dead center. This is a cycle. So all these things 1 to 2, 2 to 3, 3 to 4, 4 to 5, 5 to 1 happens in this 2 cycles whatever we do. 2 times the stroke length.

Dual Combustion Cycle

Referring to the p-V and T-s diagrams,

Heat supplied: $Q_{sup} = mC_v(T_3 - T_2) + mC_p(T_4 - T_3)$

Heat rejected: $Q_{rej} = mC_v(T_5 - T_1)$

Efficiency:

$$\eta = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{mC_v(T_5 - T_1)}{mC_v(T_3 - T_2) + mC_p(T_4 - T_3)}$$

$$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$

$$\eta = 1 - \frac{T_1\left[(T_5/T_1) - 1\right]}{T_2\left[(T_3/T_2) - 1\right] + \gamma T_3\left[(T_4/T_3) - 1\right]}$$

Let's define the volume ratios:

Compression ratio: $r_c = \dfrac{V_1}{V_2}$

Cut-off ratio: $\rho = \dfrac{V_4}{V_3}$

Expansion ratio: $r_e = \dfrac{V_5}{V_4}$

From the above relationship, we obtain: $\boxed{r_c = r_e \rho}$

Explosion ratio: $\alpha = \dfrac{P_3}{P_2}$

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Referring to the PV diagram and TS diagram of a dual combustion cycle

Heat supplied: $Q_{sup} = mC_v(T_3 - T_2) + mC_p(T_4 - T_3)$

Heat rejected: $Q_{rej} = mC_v(T_5 - T_1)$

Efficiency:

$$\eta = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{mC_v(T_5 - T_1)}{mC_v(T_3 - T_2) + mC_p(T_4 - T_3)}$$

$$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$

$$\eta = 1 - \frac{T_1\left[(T_5/T_1) - 1\right]}{T_2\left[(T_3/T_2) - 1\right] + \gamma T_3\left[(T_4/T_3) - 1\right]}$$

Let's define the volume ratios:

Compression ratio: $r_c = \dfrac{V_1}{V_2}$

Cut-off ratio: $\rho = \dfrac{V_4}{V_3}$

Expansion ratio: $r_e = \dfrac{V_5}{V_4}$

From the above relationship, we obtain: $\boxed{r_c = r_e \rho}$

Explosion ratio: $\boxed{\alpha = \dfrac{p_3}{p_2}}$

Dual Combustion Cycle

Recalling that:

For process 1-2 (Isentropic or reversible adiabatic compression)

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r_c^{\gamma-1} \Rightarrow T_2 = T_1 r_c^{\gamma-1}$$

For process 2-3: (Isochoric or reversible constant volume heat supply)

$$\frac{T_3}{T_2} = \frac{p_3}{p_2} = \alpha \Rightarrow T_3 = T_2\alpha = T_1 r_c^{\gamma-1}\alpha$$

For process 3-4 (Isobaric or reversible constant pressure heat supply)

$$\frac{T_4}{T_3} = \frac{V_4}{V_3} = \rho \Rightarrow T_4 = T_3\rho = T_1 r_c^{\gamma-1}\alpha\rho$$

For process 4-5 (Isentropic or reversible adiabatic expansion)

$$\frac{T_5}{T_4} = \left(\frac{V_4}{V_5}\right)^{\gamma-1} = \left(\frac{V_4/V_3}{V_5/V_3}\right)^{\gamma-1} = \left(\frac{\rho}{r_c}\right)^{\gamma-1} \Rightarrow T_5 = T_4\left(\frac{\rho}{r_c}\right)^{\gamma-1}$$

$$\Rightarrow T_5 = T_1 r_c^{\gamma-1}\alpha\rho\left(\frac{\rho}{r_c}\right)^{\gamma-1} = T_1\alpha\rho^{\gamma} \Rightarrow \frac{T_5}{T_1} = \alpha\rho^{\gamma}$$

On substitution into Eqn. (6);

$$\eta = 1 - \frac{T_1\left[\alpha\rho^{\gamma} - 1\right]}{T_1 r_c^{\gamma-1}\left[\alpha - 1\right] + \gamma T_1 r_c^{\gamma-1}\alpha\left[\rho - 1\right]}$$

$$\therefore \eta = 1 - \frac{1}{r_c^{\gamma-1}}\left[\frac{\alpha\rho^{\gamma} - 1}{(\alpha - 1) + \gamma\alpha(\rho - 1)}\right]$$

Observe that:

1. For $\rho = 1$, we will get expression for efficiency of Otto cycle.
2. For $\alpha = 1$, we will get expression for efficiency of Diesel cycle.

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So, recalling what happens in 1 to 2, it is the same repeat: isentropic, isochoric, isobaric, and isentropic. So, these are all reversible adiabatic compression, reversible adiabatic expansion, constant volume, and constant pressure. So, we try to substitute all and then try to get this final equation in this form. So, it is observed that when rho equals 1, we will get the expression for the efficiency of the Otto Cycle.

When rho equals 1, and when alpha equals 1, we try to get the response of the Diesel Cycle. So, this is why it is called the Dual Combustion Cycle.

Dual Combustion Cycle

• **Mean effective pressure (p_m or mep)**
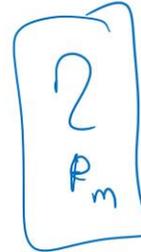
$$\therefore p_m = \frac{p_1 r_c \left\{ \left[r_c^{\gamma-1}(\alpha-1) \right] + \gamma\, r_c^{\gamma-1}\alpha(\rho-1) - (\alpha\rho^\gamma-1) \right\}}{(\gamma-1)(r_c-1)}$$

So, the mean effective pressure is also very important. So, two things are very important: efficiency and Pm, both are very important. So, Pm is the mean effective pressure. So, the mean effective pressure is again written in this form.

Comparisons: Otto, Diesel and Dual

• The Otto, Diesel and dual combustion cycles may be compared based on the

(i) same compression ratio and (ii) same maximum cycle temperature, keeping the heat rejection constant.

(i) Same compression ratio, with the same inlet conditions and the same heat rejection
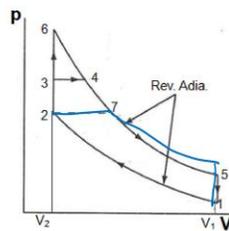
P-V DIAGRAM   T-S DIAGRAM

Now, what we will do is try to compare the Otto Cycle, Diesel Cycle, and Dual Cycle. So, the Otto Cycle, Diesel Cycle, and Dual Cycle may be compared on the same compression ratio. Same maximum cycle temperature, keeping the heat rejection constant. So, same compression ratio with the same inlet condition and the same heat rejection. So, you can see here. So, it is PV diagram. So, it is 1 to 2, 2 to 3, 3 to 4, 4 to 5 and 5 to 1. The other one is 1 to 2, 2 to 6. 6 to 5, 5 to 1.

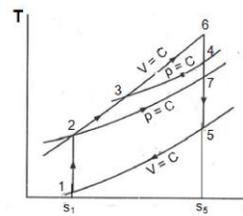The last one is 1 to 2, 2 to 7, 7 to 5, 5 to 1. So this is the for the same compression ratio with the same inlet condition and the same heat rejection we get the PV diagram. And this is the TS diagram which is corresponding to the same thing. 1 to 2, 2 to 3, 3 to 4, 4 to 7, 7 to 1, 1 to 2, 2 to 7, 7 to 5, 5 to 1.

Comparisons: Otto, Diesel and Dual

- Figure shows the Otto, Diesel and dual combustion cycles being plotted on p-V and T-s planes with the same compression ratio.
- It is observed that the area 1-2-6-5-1 which represents the net work done by the Otto cycle on p-V plane is the maximum while the area 1-2-7-5-1 which represents the work done by the Diesel cycle is the minimum.
- A similar observation is made with respect to the corresponding areas on T-s plane which represents the net heat transfer.
- Thus, it is concluded that for the same compression ratio and fixed inlet conditions and heat rejection, the Otto cycle has the maximum efficiency.

So the figure shows that Otto, Diesel and Dual Combustion Cycle being plotted on a PV and a TS diagram plane.

It is observed that the area 1 to 2, 6, 5, 1, which represents the network done by the Otto cycle. I told you 1 to 2, 2 to 6, 6 to 5, 5 to 1 is Otto cycle. So, let me write it PV diagram 1, 2, 6, 5, 1 is Otto cycle. Then it is the maximum while the area 1, 2, 7, 5, 1 is for diesel 1, 2, 7, 5, 1, 1, 2, 7, 5 and 1 is for diesel cycle. So, similar observation is made in the TS plane of auto cycle and diesel cycle. Thus, it is concluded that the same compression ratio

and fixed inlet conditions and heat rejection, auto cycle has the maximum efficiency. That is why we always go for petrol engine.
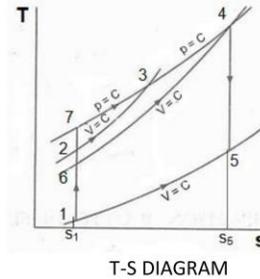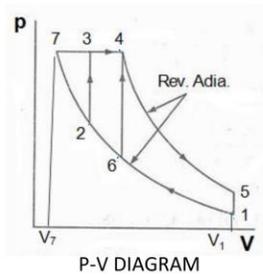
So, you can see here, Otto cycle's efficiency is greater than dual cycle than the diesel cycle, right. So, the same maximum cycle pressure and temperature with the same inlet condition and heat rejection, right. Same compression ratio here. It is same maximum cycle pressure and temperature with the same inlet condition, and the same heat rejection. So, you can see here 1, 6, 4, 5, 1. The other one can be 1, 6, 2, 3, 4, 5, 1. The last one can be 1, 2, 7, 4, 5 and 1, 3 cycles. So, here 1 let us try to write the observation as 1, 1, 7, 4, 5, 1. The other one is 1, 6, 4, 5, 1. Two cycles we are taking.

- Figure shows the p-V and T-s planes on which the Otto, Diesel and dual combustion cycles are plotted for the same maximum cycle pressure and temperature.
- It is observed that the area 1-7-4-5-1 on p-V and T-s planes is the maximum while the area 1-6-4-5-1 is the minimum.
- This means that the net work done and net heat transferred in Diesel cycle is maximum while those of Otto cycle is minimum.
- Thus, it is concluded that for the same maximum cycle pressure and temperature keeping the inlet conditions and heat rejection constant, the Diesel cycle has the maximum efficiency.

- $\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$

Figure shows that PV and TS diagram plane for auto, diesel and dual combustion cycle are plotted for the same maximum cycle pressure and temperature. So it is observed 1, 7, 4, 5, 1 is the maximum while 1, 6, 4, 5, 1 is minimum. So what are we talking about the area 1, 7, 4, 5, 1, 1, 6 is the minimum.

So, this means that the net work done and the net heat transfer in diesel engine is maximum while those of auto cycle is minimum. So, this means that the net work done and the net heat transfer in diesel cycle is maximum. That is why we all the trucks are using diesel. Of course, there are other reasons, but this can be one of the reasons. This means that the net work done and the net heat transferred in diesel cycle is maximum as compared to that of a Otto cycle.

Thus, it is concluded that for the same maximum cycle pressure and temperature, Keeping the inlet constant and heat rejection constant, the Diesel Cycle has maximum efficiency. So, it says the Diesel Cycle has greater efficiency than the Dual and Otto Cycles. If you see here, if you want to play safe, you can always choose the Dual Cycle, which comes in between. So, if you see here, in the previous one, Otto was good, and Diesel was poor. So, if you see here, Diesel is good, and Otto is poor. So, this tries to give you a comparison between the three cycles.

Brayton Cycle

- The Brayton cycle is a theoretical cycle for simple gas turbine.
- This cycle consists of two isentropic and two constant pressure processes.
- Figure shows the Brayton cycle on p-v and T-s coordinates.
- The cycle is similar to the Diesel cycle in compression and heat addition.
- The isentropic expansion of the Diesel cycle is further extended followed by constant pressure heat rejection.
- The thermal efficiency is given by,

$$\eta_{th} = 1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}$$

Now, let us go to the Brayton Cycle. The Brayton Cycle is a theoretical cycle for a simple gas turbine system. Gas turbines, I told you, are also used in power stations.

This cycle consists of two isentropic and two constant-pressure processes. The figure shows the Brayton Cycle on PV and TS coordinates. The cycle is similar to the Diesel Cycle. The Brayton Cycle is similar to the Diesel Cycle in compression and heat addition. It is very similar.

The isentropic expansion of the Diesel Cycle is further extended, followed by a constant-pressure heat rejection. The thermal efficiency is given by this formula. So, where is the difference? These are the two differences. So, the cycle is similar to the Diesel Cycle in compression and heat addition. The isentropic expansion of the Diesel Cycle is further extended, followed by a constant-pressure heat rejection. So, this is the Brayton Cycle.
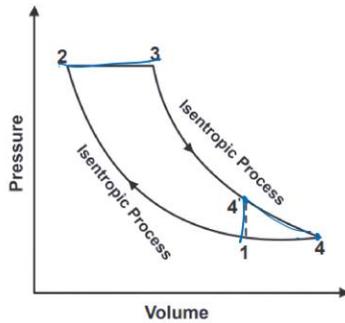
Brayton Cycle

P-V DIAGRAM
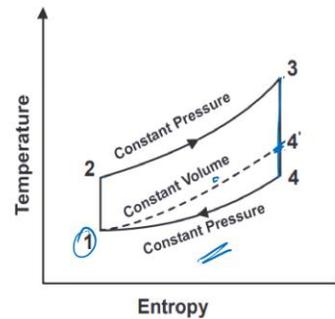
T-S DIAGRAM

So, you will see here from 1 to 2, it goes through an isentropic process. 2 to 3 is an adiabatic cycle. 3 to 4 is an isentropic process, and 4 to 1 is the expansion process, OK.

So, you will see here there are 4-dash and 4. So, if you go by the TS diagram, you can see here 2 to 3 is a constant-pressure process, and 3 to 4 is an expansion process. Wherein I tap it at 4-dash, which is intermediate. From there, I try to reduce it by constant volume going to 1, or the next one is I try to go down with a constant pressure. So, I maintain constant volume; it is 4-dash to 1. If I go with constant pressure, I come to 4, and then I go to 1. So, this is the Brayton Cycle.

Brayton Cycle

1. Isentropic Compression (1–2):

In the first step, air is compressed **adiabatically** in a compressor. This means the compression happens **without heat exchange**. As the air is compressed, its **pressure and temperature increase significantly**, while the volume decreases. This prepares the air for efficient combustion in the next stage.

2. Constant Pressure Heat Addition (2–3):

The high-pressure air now enters a **combustion chamber**, where fuel is added and burned at **constant pressure**. The combustion process causes a **sharp rise in temperature and volume**. The heat added increases the internal energy of the gas, making it ready to do work during expansion.

So, isentropic compression is from 1 to 2. In the first step, the air is compressed adiabatically in the compressor. This means that the compression happens without heat exchange. As the air is compressed, its pressure and temperature increase significantly.

While the volume decreases, this prepares the air for effective combustion in the next stage. When we talk about constant pressure and heat addition from 2 to 3, the high-pressure air now enters the combustion chamber, where fuel is added and burned at constant pressure. The combustion process causes a sharp rise in temperature and volume. The heat added increases the internal energy of the gas, which makes it ready to do work during expansion. So, please understand, the high-pressure air now enters the combustion chamber.

When the fuel is added and burned at constant pressure, because we are adding heat at constant pressure. The combustion process causes a sharp rise in temperature and volume, okay.

Brayton Cycle

3. Isentropic Expansion (3–4):

The high-temperature, high-pressure gases expand **adiabatically** in a **turbine**, performing **work on the turbine blades**. As the gases expand, their **pressure and temperature drop**, and they transfer energy to generate useful work. This is the **power-producing** phase of the cycle.

4. Constant Pressure Heat Rejection (4–1):

After expansion, the gases are released to the surroundings (in open cycles) or cooled in a heat exchanger (in closed cycles) at **constant pressure**. The **temperature decreases**, completing the cycle and preparing the air for the next compression stage.

So then, it is isentropic expansion. The high-temperature, high-pressure gas expands adiabatically in a turbine, performing work on the turbine blade. As the gas expands, the pressure and temperature fall, and there is an energy transfer to useful work.

This is called as a power producing phase of a cycle. So 3 to 4 is isentropic. The constant pressure rejection is after the expansion, the gas are released to the surrounding open

cylinder. If it is closed cylinder, it is cooled and it is retaken into the system. So, cooled in a heat exchanger in a closed loop system at a constant pressure, the temperature decreases completing the cycle and preparing the air for the next compression cycle, ok.

So, this is Bratton cycle. So, Bratton cycle is this where in which it talks about isoentropic compression, constant pressure heat addition, the isentropic expansion and constant pressure heat rejection.

Deviation of Actual Cycles

(a) Compression and expansion are not friction less adiabatic processes. A Certain amount of friction is always present and there is considerable heat transfer between the gases and cylinder wall.
(b) Combustion does not occur either at constant volume or at constant pressure.
(c) The thermodynamics properties of the gases after combustion are different than those of the fuel-air mixture before combustion.
(d) The combustion may be incomplete.
(e) The specific heats of working fluid are not constant but increase with temperature.
(f) The cylinder pressure during exhaust process is higher than the atmosphere. As a result, more work has to be done by the piston on the gases to expel them out of the cylinder, than work done by the gases on the piston during the intake stroke.
This difference in work, called pumping work, is represented by the pumping loop shown by hatched area.
Note that this work is negative and represents loss of work called pumping loss.

So now, let us see how are these things Deviated from the Actual Cycles. Compression, expansion are not frictionless adiabatic process. A certain amount of friction is always present.

There is considerable heat transfer between the gas and the cylinder wall. So there is a residual temperature. This residual temperature, we don't know what amount of residual temperature is there. Now you restart the new cycle. So the old residual, while the piston is moving to a certain height itself, can raise the temperature very high.

So the combustion can happen prior what was expected. So that's what is a big deviation. The combustion does not occur immediately. Either at constant volume or at a constant pressure. It never happens.

This brings the next deviation. The thermodynamic property of the gas after combustion are different than those of the fuel air mixture before combustion. So the air density reduces. The air property reduces. The air becomes light.

So the thermodynamic property, so for example, while you are compressing, the air would have come at a certain speed. After the combustion is over, it exhausts at a much faster rate. Possible. So then there is a thermodynamic property of the working fluid change. The combustion may be incomplete.

Not all the diesel particles or the air particles get burnt. So now, once it does not get burnt, it again tries to bring you residue and other things. The specific heat of the working fluid is never constant. It increases with temperature. How much does it increase?

What is the exponential increase? Very hard to find out. So now people are trying to use glass engines and try to see the combustion. How is it happening? How is it propagating through a laser?

So they are trying to monitor very precisely, but still it cannot be found out by one laser. So they have lasers in multiple planes. So in one plane, they try to take the temperature distribution and see how a wave propagates. So that's a challenge. Even now, there is a lot of work going on.

And big Otto industries work more and more on how to improve the efficiency of combustion. The cylinder pressure during the exhaust process is higher than the atmosphere. As a result, more work has to be done by the piston on the gas to expel it out of the cylinder. The cylinder pressure during the exhaust process is much higher than the atmosphere. So, there is atmospheric pressure, which is constant.

Now, assume you are forcing air to go through. So, this fellow will resist, right? As a result, more work has to be done so that the fuel can go inside easily. For example, you have a crowd of people there. They are standing.

Now, you are pushing one person inside. So, when you try to push, you have to push him with more energy so that he gets into the crowd. More work has to be done by the piston on the gas to expel it out. So, there is a deviation.

To Recapitulate

- What do we understand by Gas Power Cycles? What are its various types?
- What are Air Standard Power Cycles? State their characteristics.
- What is a Carnot Cycle? Explain its features and applications.
- Explain the Stirling Cycle alongwith its characteristics.
- What do you understand by an Otto Cycle?
- State and discuss about the Diesel Cycle.
- Differentiate between Actual Diesel and the Otto Engines.
- What is a Dual Combustion Cycle in Thermodynamics?
- Compare the Otto, Diesel and Dual Cycles.
- What do you understand by Brayton Cycle? What are its features.
- How do Actual Cycles deviate from Air Standard Cycles?

Handwritten notes:
- truck → 50 km/h
  → 100 tonnes
  torque
- Race → 200 km/h
  torque →
  why race have frequ fillig
- Diesel Engine → loco
  → mileage
  why is it so?

So, friends, in these two lectures, what we saw was: what is a Gas Power Cycle, what are the different types, what is an Air Standard Power Cycle, and what are its characteristics.

Then, what is a Carnot Cycle and its features? Stirling Cycle and its features, then we understood what the Otto Cycle, Diesel Cycle, and Dual Combustion Cycle are. Then, what is the comparison of Otto, Diesel, and Dual Cycle? Finally, we saw what a Brayton Cycle is. Before we conclude, we also saw that whatever happens in reality, there is a major deviation from the theory. So, that is what we saw in the last slide. So, friends, now I have a small observation task for you to do since you have studied all these cycles.

So, look at a truck traveling at 50 kilometers per hour with a tonnage of 100 tons. It is going at 50 kilometers per hour. Now, try to see what torque it will generate for its motion with this load. Just a simple calculation—you can try to see what the torque will be and what energy is required for it to carry 100 tons on its back and run at 50 kilometers per hour. Just a simple calculation so that you understand the energy and other things we are talking about. Try to look at a race car traveling at 200 kilometers per hour.

And what is its torque? You can do some simple calculations with assumptions or directly look at some specifications and find out. Why does the race car require frequent refueling, whatever it may be, right? The third thing is, when we talk about diesel engines used in locomotives, what should their mileage be? Why is it so?

For example, if the mileage is high, why is it high? If it is low, why is it low? And then, if it is the same as a normal car, why is it so? So, these three things—if you start looking into them—then you will try to understand what makes this entire thermodynamics very important for an engineer.

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These are the references we have used in preparing this chapter.

Thank you very much.