Basics of Mechanical Engineering-3

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Week 03

Lecture 13: Gas Cycles in Thermodynamics Part 1 of 2

Welcome to yet another new lecture on Gas Cycles in Thermodynamics as part of Basic Mechanical Engineering 3.

Contents
- Gas Power Cycles (Introduction)
- Air Standard Power Cycles
- Carnot Cycle
- Stirling Cycle
- Otto Cycle

The content in this lecture will be: we will introduce Gas Power Cycles. Basically, how does a power cycle run using gas? That means, how do you generate power? Then, we will look into Air Standard Power Cycles. Then, the Carnot Cycle, Stirling Cycle, and Otto Cycle. The Otto Cycle, as you know, is used in automobiles. Then, the Diesel Cycle, followed by a comparison between the actual Diesel and Otto engines. Then, we will
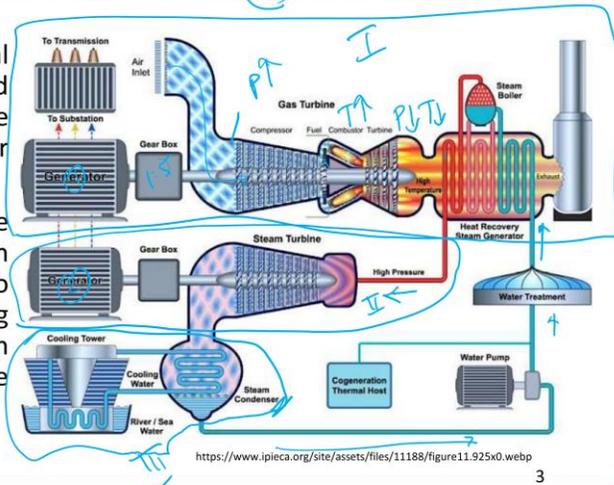
examine the Dual, meaning a mix of two, the Dual Combustion Cycle. Then, a comparison of the Otto, Diesel, and Dual Cycles. Finally, we will explore the Brayton Cycle and the derivation associated with actual cycles.

A Gas Power Cycle is a thermodynamic cycle that uses gas as its working fluid to convert heat into mechanical energy. That means the gas is heated. Right.

And it is taken to a higher temperature. To start, what happens is you take the air inlet. Right. The air inlet allows air to go inside. Then, it gets compressed.

It is getting compressed where the pressure increases and then it was allowed. To go through a carburetor, carburetor where there is a mixture of fuel and air happens, then it is, after this it is burnt and it is sent to turbine. So, here the T increases, P increases, here what happens, P decreases and the T also decreases. By doing so, it is trying to turn the turbine blades. Now, when it tries to turn the turbine blades, the output of the turbine blade is taken to a gearbox where they have a ratio 1 is to 5, 1 is to 10 or something.

So, they accelerate or they amplify. Gearbox is nothing but a mechanical amplifier or you can say multiplying agent or a dividing agent. So, you can increase it or decrease the speed and where in which you try to make a compromise on your torque. So, then gearbox is attached from a gearbox you try to take it to a generator. Right.

This generator, electricity, whatever is there is sent to a substation. From a substation, it transmits. Right. So now we have left the story here. So what happens to the gas which is there here?

So this gas, whatever is, is of very high temperature. So it tries to heat the water which is through this pipe. It is water through this pipe. So now water whichever is there is getting heated and it converts into a steam. The steam is generated through this pipes and this pipe is trying to take it to a steam goes up and from there it goes to a boiler.

So in a boiler there is a transfer of heat which is happening. So, if you look at it, it is a closed loop. So, there is water. Okay, let us take water from here. There is water coming from here.

So, then it is the water is getting treated. The treated water is going through a pipe and this pipe is going to a steam boiler. So, here there is a cold water and now whatever is heat there on the top it is it is throwing the heat now. So, there is a transition happening between the the cold and the hot. So, whatever it is the hot so, then that tries to come into high pressure and high temperature it comes through this pipe and then that tries to hit the turbine blades through this turbine blades again gearbox gearbox to generator.

Okay, so now you can see here there is generator 1, generator 2, a larger turbine, a smaller turbine. So whatever is the steam gets condensed and if it is still heat then it is sent to a sink where it is passing through a coolant tower and it comes to room temperature. From the cooling tower it gets into back into the sys circuit. Okay, so you can see here steam is getting condensed. So whatever comes from here, the content steam becomes water and that water goes here.

So then this is a independent circuit cooling tower. This is an independent circuit you see here. So the water whatever comes from here. gets deposited down and it gets into the reaction. And while the heated water, the steam comes down, if this is trying to do a heat transfer to this liquid, whatever is there, that liquid gets cooled through the cooling tower.

Why? Because whatever comes down, if it goes with a very high temperature, then here there will be one more amount of boiling. So this becomes an independent circuit. This is another circuit, but it is connected to the previous one. And this part is completely a different one.

So, there are 3: 1, 2, and 3. The third system is only for cooling. The second system is a small version of the large system. So, the gas power cycle is fundamental to the modern

mechanical and aerospace industry, forming the backbone of numerous power generation and propulsion systems. So, in aerospace, we always use gas power cycles.

So, basically, you will have all these things. And if you see this, it's very simple: you have a working fluid called water. So, this water will be converted into steam. When you convert it into steam, there are only two possibilities. One, you increase the temperature.

Next, you have to adjust the pressure. So, these are the two things. And if you assume that it is a closed-loop system, there is no change in the volume of water. So, the water, when heated, becomes steam. When it is steam, the temperature rises. And in between, what you do is pass it through a turbine or pump it faster, and the pressure also increases significantly.

So, when these temperatures and pressures are very high, you have to bring them down to normal temperature and pressure. So, when you have to bring it to normal, you have to do work. So, that is how the work is done here; that is all. Nothing more. Now, I think you should be able to understand.

Now, replace water with gas. That is all. So, water, steam, temperature, pressure, increase, decrease. So, when it is increased, you try to heat it. When it is decreased, you try to convert it into normal water and then take it back into the system.

Right. The gas power cycles are fundamental to modern mechanical and aerospace engineering principles. They form the backbone of numerous power generation and propulsion systems. These cycles describe the thermodynamic process by which heat energy is converted into mechanical work using a working fluid. That's what I said. You have a working fluid. This working fluid is where you manipulate pressure and temperature. That's all. So, typically, air and combustion gases remain in the gaseous state throughout the cycle.

Gas Power Cycles

- Gas power cycles are idealized models that help engineers understand, analyze and optimize real-life engines such as internal combustion engines, jet engines and gas turbines.
- They are categorized into open and closed cycles, with the Otto, Diesel, Brayton and Atkinson cycles being the most prominent.
- Each of these cycles models a different type of engine operation, capturing the essential thermodynamic steps such as compression, combustion (or heat addition), expansion, and exhaust.
- By analyzing these processes using assumptions like ideal gas behavior, isentropic efficiency, and constant specific heats, engineers can predict engine performance metrics such as thermal efficiency, work output, and specific fuel consumption.
- Although ideal gas power cycles simplify real engine behavior, they provide crucial insights into the trade-offs involved in engine design—such as the balance between efficiency, power output, and complexity.

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They are categorized into both open and closed cycles, with the Otto, Diesel, Brayton, and Atkinson cycles being the most prominent ones. Each of these cycles models a different type of engine operation, capturing the essential thermodynamic steps, such as compression, combustion, expansion, and exhaust. Four steps, very easy. You have air. This air must be compressed.

You have air confined to a volume; it must be expanded. Then, when you compress, and when do you switch to expansion? There must be a process called combustion. Blast. Combustion.

Once this combustion happens, the expansion happens. Whatever is left out in the system has to be exhausted. Four systems. Four steps, right? When you talk about compression expansion, you will try to have a PV diagram, you will try to have a TS diagram, right?

By analyzing these processes using assumptions like ideal gas behavior, isentropic, we have seen all these things, isentropic efficiency, constant specific heat, Engineers can predict the engine performance metrics such as thermal efficiency. This is very important. In the examination, you will be asked only these things. How do you calculate thermal efficiency?

How do you calculate the work output? How do you calculate the specific fuel consumption? Specific fuel consumption is one litre of petrol or one litre of diesel. How far it is going? For example, how many kilometres it is going?

That is specific fuel consumption. So, these are the three outputs we used to take in the system, where we assume that it exhibits ideal gas behavior, is isentropic in nature, and has constant specific heat. Although ideal gas power cycles simplify real engine behavior, They provide crucial insight into the trade-offs involved in engine design, such as the balance between efficiency, power, and complexity. So here, when I talk about thermal efficiency, we also try to calculate work output and power output. This is also there.

Gas Power Cycles

- A power cycle continuously converts heat (energy .released by the burning of fuel) into work (shaft work), in which a working fluid repeatedly performs a succession of processes.
- In the vapor power cycle, the working fluid, which is water, undergoes a change of phase.
- With growing demands for energy efficiency and environmental sustainability, understanding gas power cycles remains a cornerstone in developing advanced, cleaner, and more efficient energy systems.
- In addition to their foundational role in engine design and thermodynamic analysis, gas power cycles serve as essential tools for evaluating the performance limits and efficiency potentials of real-world machines.

The power cycle continuously converts heat into work, in which the working fluid repeatedly performs a succession of processes. Why? Because water is a closed-loop system. Water heats, steams, you cool it, it becomes water, then you heat it.

It continues in a cycle. In the vapor power cycle, the working fluid, which is water, undergoes a phase change. What is the phase? Liquid phase to gaseous phase. With growing demand for energy efficiency and environmental sustainability, understanding gas power cycles remains a cornerstone in developing advanced, cleaner, and more efficient systems.

In addition to this foundational role in engine design and thermodynamic analysis, the gas power cycle serves as an essential tool for evaluating the performance limits and efficiency potential of real-world machines.

Gas Power Cycles

- Power cycles are those thermodynamic cycles in which the heat energy is partly absorbed to produce net mechanical work.
- The power cycles are classified into:

(i) Gas power cycles

They use gas as the working fluid and the gas does not undergo change of phase. Ex: IC Engines, Gas Turbines.

(ii) Vapour power cycles

They use vapour as the working substance and the vapour undergoes phase change. Ex: Steam Engines, Steam Turbines.

The power cycle is a thermodynamic cycle in which heat energy is partially absorbed to produce net mechanical energy. The power cycles can be classified easily into two types: gas and vapor. In the gas cycle, we use gas as the working fluid. The gas does not undergo a change of phase.

So, IC engines and gas turbines work on gas. When we talk about vapor pressure, we always try to take water as the working fluid, right? Water is a working fluid, but sometimes you can use other chemicals also. They use vapor as the working substance, and the vapor undergoes a change in phase. That is why it is called the vapor power cycle.

So, steam engines, steam turbines. So, these are different. The power cycle, which assumes air as the working fluid, is known as the Air Standard Power Cycle. So, we saw vapor, we saw gas, right? Two systems we saw.

Air Standard Power Cycles

The power cycles which assume air as the working substance are known as Air Standard Power Cycles.

The following assumptions are made for the analysis of air standard cycles:

1) The air of fixed mass undergoes a cyclic process.
2) The air behaves like a perfect gas.
3) Specific heats of air remain constant during the cycle.
4) Thermodynamic processes of the cycle are reversible.
5) The combustion process is replaced by a heat-addition process from an external source.
6) The exhaust process is replaced by a heat-rejection process which brings the state of air to its initial state, thus completing the cycle.
7) The compression and expansion processes undergo reversible adiabatic (isentropic) processes.
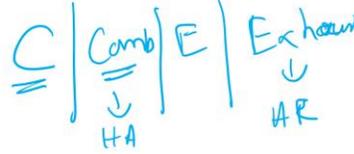
Now, we are trying to say we assume air. In the vapor, we try to take gas. A liquid where there is a change in phase. In a gas, we try to use gas as a fluid where there is no phase change. Gas cannot undergo a phase change, right?

So, of course, if you can reach a negative temperature, then it can become a liquid. When you go further down, it can never become a solid, but it can become a liquid very fast. So, the power cycle which assumes air as the working substance is known as the air standard power cycle. The following assumptions are made for the analysis of air standard cycles. The air of fixed mass undergoes a cyclic process.

The air of a fixed mass. Air in mass. The air behaves like a perfect gas. It does not have any molecules. It does not give any friction.

There should not be water, all those things. The specific heat of air remains constant all through the cycle. It is an assumption. The thermodynamic process of a cycle are reversible. The combustion process is replaced by heat addition process from an external source.

The combustion process is replaced because when combustion happens, so from compression, combustion expansion will go, right, and then exhaust. You try to apply heat from outside. The exhaust process is replaced by a heat rejected process, which brings the state of the air to the initial state, thus completing the cycle. So, as I told you compression, then it is combustion, then it is expansion, then it is exhaust, right.

Compression and this is combustion, right. In combustion, there is a heat addition. Exhaust, there is a heat rejection. The compression and expansion process undergoes reversible adiabatic process.
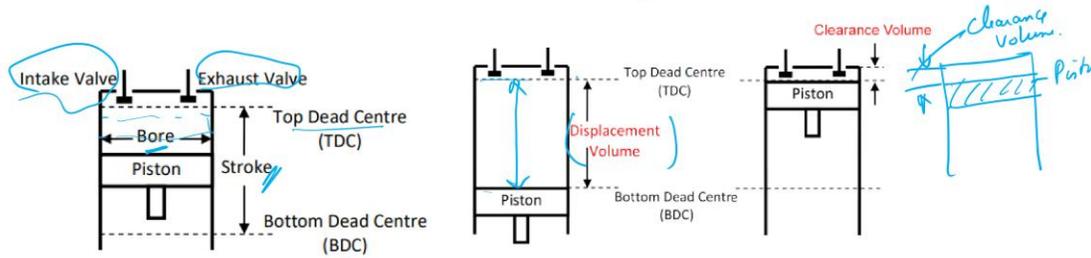
So the air standard power cycle system looks like this. So you will have this is a cylinder. The internal of a cylinder is called as a bore. Cylinder, the hole, right? You have a water bottle. The inner side of the water bottle is called as a bore, right? Then what will happen is there is a piston which is to prevent the air which is stored inside the bore to be constant, right?

So the piston is a moving member, right? So depending upon the heat, there can be an expansion or when the piston movement, there can be a compression. So for the air to come into the system, you have an inlet valve and for the exhaust to go out, it is called as the exhaust valve. So, the top one is called as TDC, top dead center. The bottom one is called as the BDC, bottom dead center.

So, what it means is the piston can go very close to the top dead center and the piston can come to the furthermost in the cylinder is the bottom dead system. The complete distance between the TDS to BDS is called as the stroke. So, when the piston is at the topmost position, there will be almost zero air. So now what happens when the piston is moving

down, it is opening the inlet valve and it is trying to suck through inlet valve the air inside the system.

And, once the piston is returning back to the TDC, the exhaust valve will open, and all the burnt materials will be expelled. Okay, so this is the air-standard power cycle. So, again, here is compression. You will have combustion, then expansion, then exhaust— four stages, okay? So, here, if you see, the TDC is at the top, and the BDC is at the bottom.

So, this one is called the total volume. This is the stroke length, okay. The total volume of air it can take is called the displacement volume, okay. So, between the TDC and the cylinder top-end, between this and here, this is called the piston, right? So, this small area is called the clearance volume. Okay. These are the terminologies used in reciprocating engines.

So, some of the important terminologies related to reciprocating engines are shown in the figure: bore. The diameter of the piston is the bore. True.

Because whatever is there, the piston also, because if you don't have the piston tight, then there will be an air leak, which is happening. Some important terminologies related to the reciprocating engine are shown in the figure and explained as follows. Bore: it is the

diameter of the piston. Top dead center: it is the position of the piston when it forms the smallest volume in the cylinder. So, it is the top dead, smallest volume.


And when you say stroke, stroke is the distance between the top dead center and the bottom dead center. And the piston travels one stroke in one direction. The length is called a stroke. Then, what is an intake valve? It allows the air or the air-fuel mixture to be drawn into the cylinder.

It allows the air inlet valve. It allows the air or the air-fuel mixture. Air is plain air. Air-fuel mixture means air plus some volatile material when it enters into it. Air-fuel mixture to be drawn into the cylinder.

Then, the exhaust valve, after combustion is over, allows the combusted products to be expelled from the cylinder. So, then there is something called a clearance volume. The clearance volume is the minimum volume of the cylinder when the piston is at the topmost position or top dead center.

Air Standard Power Cycles

- **Displacement volume:** The Displacement Volume (or Stroke Volume) is the volume equal to the difference in total volume and clearance volume of the cycle.

- **Swept volume:** When the piston moves from TDC to BDC, the volume displaced by the piston is called Swept Volume

- **Compression ratio:** The Compression Ratio r_c of an engine is the ratio of the maximum volume to the minimum volume formed in the cylinder.

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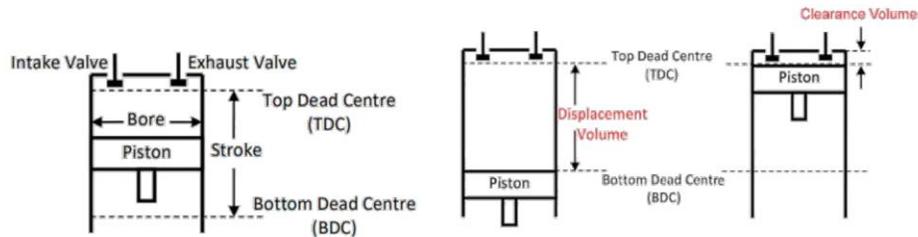
The displacement volume is the distance between the TDC and the top end of the BDC. It is the volume equal to the difference between the total volume and the clearance volume. Swept volume is the piston moving from TDC to BDC or BDC to TDC. When there is movement and expansion happening, then there is something called a compression ratio. So, the compression ratio is given as RC. It is the ratio between the maximum volume and the minimum volume formed inside the cylinder. Maximum volume divided by the minimum volume in the cylinder—that is the ratio, okay. So, all these things we have seen are part of the air standard power cycle, right? Here, there are four processes that we also saw.
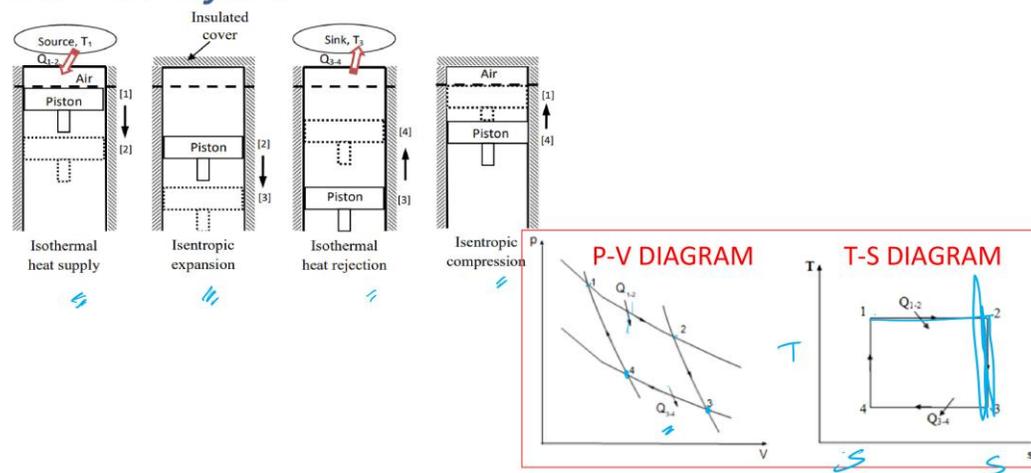
Carnot Cycle

Carnot cycle is a totally reversible cycle consisting of two isothermal and two isentropic (reversible adiabatic) processes.

- Carnot cycle can be executed in a closed system or a steady- flow device. In this cycle, either a gas or a vapor can be used as the working fluid.
- The Carnot cycle is the most efficient cycle that can work between a heat source at temperature T_1 and a sink at temperature T_2.
- The Carnot cycle cannot be built in reality because it is not a practical cycle.
- However, the Carnot cycle is used as a standard against which the actual or ideal cycles can be compared. It was invented by Nicolas Leonard Sadi Carnot in the year 1824.

Next, let us get into the Carnot Cycle. The Carnot cycle is a totally reversible cycle consisting of two isothermal and two isentropic processes, wherein the isentropic process is always a reversible adiabatic process. The Carnot cycle can be executed in a closed system or a steady-flow device. In this cycle, we either use gas or vapor as the working fluid in Carnot. So, the Carnot cycle is the most efficient cycle.

That can work between the heat source T1 and the sink T3. It's the most efficient engine, the Carnot engine. The Carnot cycle cannot be built in reality because it is not a practical cycle. However, the Carnot cycle is used as a standard against which the actual and ideal cycles are compared.

So, the Carnot cycle is again divided into four processes: isothermal heat supply, isentropic expansion, isothermal heat rejection, and isentropic compression. When there is a heat source and when the cylinder is at its topmost position. At the topmost position, what is happening is that heat is applied, then immediately, the piston will start expanding. So, there is an increase in volume, and the piston keeps moving down. Then, the piston further keeps moving down from 2 to 3, where there is an isentropic expansion. After reaching state 3, what is happening now? There will be heat that is getting rejected.

So, the piston is moving upward. So, from 3 to 4, there is compression, and from 4 to 1, there is another compression. So, 3 to 4 is isothermal heat rejection because heat is Q out.

So, isothermal heat rejection and the other one, from 4 to 1, is isentropic compression. So, the TS diagram for the entire system is drawn here.

T is constant from 1 to 2, and from 3 to 4, the T is reduced. So, from 1 to 2, there is a constant temperature, and the entropy changes. From 2 to 3, there is no entropy change, but the temperature drops drastically. From 3 to 4, there is a constant temperature, and there is heat which is getting rejected. And 4 to 1 is the isentropic compression, wherein the entropy is the same.

Carnot Cycle

- **Isothermal Expansion (1–2):**

  In this process, the gas is placed in contact with a high-temperature heat source and expands slowly while maintaining a constant temperature T_H. As it expands, it absorbs heat energy from the source. Since the temperature remains constant, the internal energy of the gas does not change, and all the absorbed heat is converted into work done by the gas on the surroundings.

- **Adiabatic Expansion (2–3):**

  Next, the gas is thermally insulated so that no heat can enter or leave the system. It continues to expand, and in doing so, its temperature falls from T_H to T_C. Because no heat is added or removed, the gas uses its own internal energy to do work. This results in a decrease in temperature and pressure, but the entropy stays constant.

So, isothermal expansion: In this process, the gas is placed in contact with the high-temperature heat source and expands slowly while maintaining the constant temperature TH. As it expands, it absorbs heat energy from the source. Since the temperature remains constant, the internal energy of the gas does not change. And, all the absorbed heat is converted into work done by the gas on the surroundings. So, since the temperature remains constant, the internal energy of the gas does not change.

The internal energy of the gas does not change. And, all the absorbed heat is converted into work by the gas on the surroundings. So, that happens during isothermal expansion. 1 to 2, heat is in. 2 to 3, there is an adiabatic expansion.

Next, the gas is thermally insulated. So that no heat can enter or leave the system. It continues to expand and, in doing so, its temperature falls from TH to TC. Because no heat is added or removed, the gas uses its own internal energy for work. This results in a decrease in temperature and pressure, but the entropy stays constant.

Because this is S, this is S. The 2, 3 is constant. 4, 1 is also constant. The difference is delta S.

Carnot Cycle

- **Isothermal Compression (3–4):**

  Now the gas comes into contact with a cold reservoir at constant temperature T_C. It is slowly compressed, and during this process, it releases heat to the cold reservoir. The temperature of the gas remains constant throughout, so the work done **on** the gas is equal to the amount of heat it gives away. Again, the internal energy does not change.

- **Adiabatic Compression (4–1):**

  Finally, the gas is again insulated, and it is compressed without exchanging heat with the surroundings. As the gas is compressed, its temperature rises from T_C back to T_H. The work done on the gas increases its internal energy, raising both its temperature and pressure. The process ends where it began, completing the cycle.

Next is isothermal compression from 3 to 4. Now, the gas comes in contact with the cold reservoir at a constant temperature TC. It is slowly compressed, and during this process, it releases heat to the cold reservoir.

The temperature of the gas remains constant throughout. So, the work done on the gas is equal to the amount of heat it gives away. Again, the internal energy does not change. U does not change. The last one is adiabatic compression.

Finally, the gas is again insulated, and it is compressed without exchanging heat with the surroundings. As the gas is compressed, the temperature increases from TCE to TH. The work done on the gas increases its internal energy, raising both its temperature and pressure. The process ends where it begins and completes a cycle. So, this is what it is: 1 to 2, 2 to 3, 3 to 4, 4 to 1. Heat rejection, heat addition, heat rejection. This is compression, this is compression, and this is expansion.

Carnot Cycle

- Referring to the P-V and T-S diagrams shown:

P-V DIAGRAM **T-S DIAGRAM**

Heat supplied: $Q_{sup} = Q_{1-2} = RT_1 \ln(V_2/V_1)$

Heat rejected: $Q_{rej} = Q_{3-4} = RT_3 \ln(V_3/V_4)$

For the process 2–3 (Isentropic expansion),

$$\frac{V_2}{V_3} = \left(\frac{T_3}{T_1}\right)^{\frac{1}{\gamma-1}} \Rightarrow \frac{V_2}{V_1} = \frac{V_3}{V_4}$$

$$\eta = 1 - \frac{Q_{rej}}{Q_{sup}} = 1 - \frac{RT_3(\ln V_3/V_4)}{RT1(\ln V_2/V_1)}$$

$$\therefore \eta = 1 - (T_1/T_3)$$

$$\eta = 1 - \frac{Q_{rej}}{Q_{sup}}$$

17

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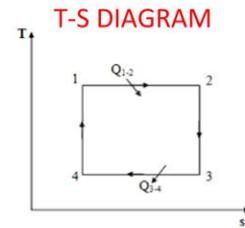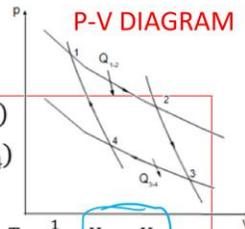
Now, let us try to refer to the PV diagram and TS diagram. So, this is the PV diagram. In the PV diagram and TS diagram,

Stirling Cycle

- Stirling cycle consists of two reversible isothermal and two constant volume (isochoric) processes.

- It is a totally reversible cycle, like Carnot cycle, as the heat-addition and heat-rejection processes take place isothermally during the cycle.
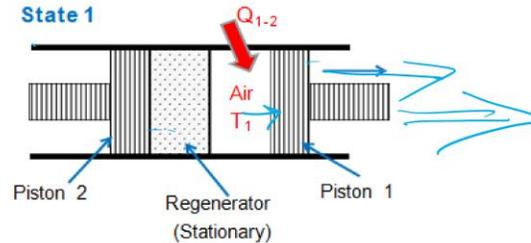
Schematic of Stirling cycle showing state1 of the working fluid

So, Stirling Cycle. Stirling cycle consists of two reversible. See, here also we saw, Otto cycle is also reversible. Totally reversible cycle. Stirling Cycle consists of also two reversible isothermal and two constant volume isochoric processes involved.

It is a totally reversible cycle like Carnot cycle. As the heat addition and the heat rejection processes take place isothermally during the cycle. The heat rejection and the heat addition. Heat addition and heat rejection processes take place isothermally during the cycle. Say, for example, you have a piston, right, you have a cylinder, a cylinder has an open end. So, you have two pistons; these pistons move, right.

So, here you have air, air is at a temperature T1, then you have a regenerator stationary, right, and then you will have pistons P1 and P2. So, this moves this side.

Stirling Cycle

- The working of Stirling cycle in a closed system is explained with the help of a schematic diagram shown in Figure The system consists of a cylinder with two pistons on each side and a regenerator in the middle.
- The regenerator acts as a temporary storage of thermal storage. All the thermodynamic processes of Stirling cycle are shown on p-V and T-s planes in Figure.
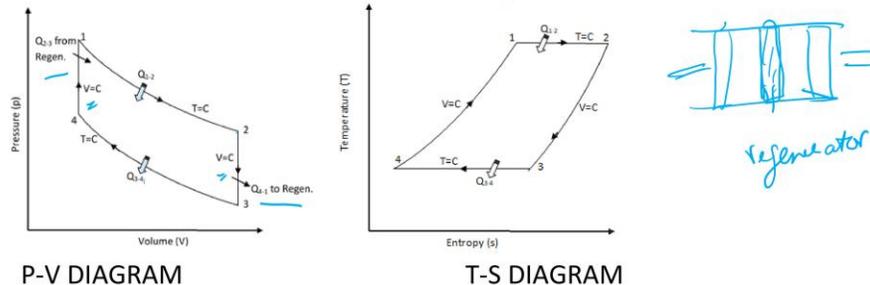
P-V DIAGRAM   **T-S DIAGRAM**

The working of a Stirling cycle is a closed system, is explained with the help of a PV diagram and a TS diagram. The system consists of a cylinder with two piston, one cylinder with two piston, right, on each sides of a regenerator in the middle. So, there is a regenerator in the regenerator.

There is a regenerator in the middle. The regenerator which is there in the middle acts like a temporary storage of thermal. So, this is regenerator which is a stationary one which is inside stationary right it is not moving. All the thermodynamic processes of Stirling cycle are shown in the PV diagram and the TS diagram. So 1 to 2 there is a heat in and then 3 to 4 there is a heat reject right. So 2 to 3 and 3 to 4 are adiabatic cycles. So 4 to 3 to region and 2 to 3 also region. And here V = C.

Stirling Cycle

P, T, V

- **Isothermal Expansion (1–2):**

  In this process, the working gas (often helium or air) is heated while in contact with a hot source at constant high temperature T_H. As the gas expands, it absorbs heat and does work by pushing a piston outward. Since the temperature stays constant, the heat added is fully converted into work, and the pressure of the gas decreases as its volume increases.

- **Isochoric (Constant Volume) Heat Removal (2–3):**

  After the expansion, the gas is moved to a cooler region (often through a regenerator), and its temperature is reduced from T_H to T_C **without changing the volume**. During this step, the gas gives off heat to the regenerator or the surroundings. Since volume is constant, no work is done, and the internal energy decrease is entirely due to heat loss.
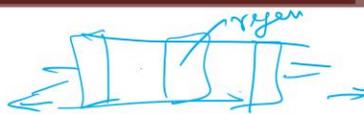
In this process, the working gas is heated. The gas air which is there is heated, right? While it contacts the heat source at a constant temperature TH. As the gas expands, it absorbs heat and does work by pushing the piston outward. So, when heat is given, this fellow expands. So, this piston is dragged along this direction. It absorbs heat and does work by pushing the piston outward.

Since the temperature stays constant—because it is an isothermal process—the heat added is fully converted into work, and the pressure of the gas decreases as its volume increases. So, as I told you, there are only pressure, temperature, and volume. That is all. If the pressure of the gas decreases as its volume increases, then an isochoric process occurs where you have constant-volume heat removal. After the expansion, the gas is moved to a cooler region.

After the expansion, what is expansion? After the piston is completely dragged outward in expansion, the gas is moved to the cooler region. Often through the regenerator. So, now, the cooler region. So, it moves to the other side, to the cooler region, and the temperature is reduced from TH to TC without changing its volume.

So, whatever is there, it is pressed. So, there is a regenerator. The air goes to the other side. During this step, the gas gives off heat to the regenerator or to the surroundings. When it passes through, the regenerator, which is there, absorbs heat. Since the volume is constant, no work is done, and the internal energy decreases. It is entirely due to heat loss.

Stirling Cycle

- **Isothermal Compression (3–4):**

  Now, the gas is compressed at the cooler temperature T_C. As the piston moves inward, work is done **on** the gas, but since the temperature is constant, the gas releases heat equal to the work input. This process increases the pressure and decreases the volume, preparing the gas for the next phase.

- **Isochoric (Constant Volume) Heat Addition (4–1):**

  In the final process, the gas is transferred back to the hot region (via the regenerator), where its temperature increases from T_C back to T_H, **without any change in volume**. The heat added here comes mostly from the regenerator, improving the cycle's efficiency. Again, since the volume is constant, no work is done in this step.

Then, let us go to the isothermal compression. Then, from the other side, you are trying to compress. So, this is regeneration. This is a piston. This is a piston that is moving. This is also moving. So, from one side to the other side, it is going. Now, the gas is compressed at a cooler temperature, Tc. It is compressed. As the piston moves inward, the work is done on the gas here. But the temperature is constant. So the gas releases heat equal to the work input. The process increases the pressure and decreases the volume preparing the gas to the next phase.

So from here it goes to the next phase. Isochronic process that means to say where there is a constant volume in this in the final process the gas is transferred back to the hot region. So, it came to cold, f rom cold it goes to hot region, but the volume is constant. Where its temperature increases from Tc to Th without changing the volume. Before also you saw without changing the volume.

In 2 to 3 and 4 to 1 there is no volume change. The heat is added here comes mostly from the regenerator improves the cyclic efficiency. So since the volume is constant so no work is done during this process. So, if you go back and try to see the diagram, so you can see PV diagram 1 to 2, then 2 to 3 is Q out, this is regeneration process, Q to regeneration process, then it is rejection, then it is focused on regeneration process. If you draw the TS diagram for this, it is almost the same.

Stirling Cycle

Features of Stirling Cycle

- It is an altered version of Carnot cycle that comprises of two constant volume regeneration processes.
- The processes are not reversible in reality.
- The weight to power ratio is high.
- However, because of their higher efficiency potential and better emission control, Stirling engines with modifications have been tried to compete with the petrol or diesel engines.

So, what are the features of a Stirling cycle? It is an alternative version of the Carnot engine that comprises two constant-volume regeneration processes. Keep that in mind. The processes are not reversible. Okay.

The weight-to-power ratio is very high. So, we always use the Stirling cycle where you want a high weight-to-power ratio. However, because of their high efficiency potential and better emission control, Stirling engines with modifications have been tried to compete with petrol or diesel engines, but it has not been easy. So, if you understand this cycle, we have seen the Stirling cycle, which has two isothermal processes: isothermal expansion, isothermal compression, isochoric heat removal, and isochoric heat addition. So, these are the four steps.

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

Heat supplied: $Q_{sup} = Q_{1-2} = RT_1 \ln \dfrac{v_2}{v_1}$

Heat rejected: $Q_{rej} = Q_{3-4} = RT_3 \ln \dfrac{v_3}{v_4}$

From p-v diagram, $\dfrac{v_2}{v_1} = \dfrac{v_3}{v_4}$

$\eta = 1 - \dfrac{Q_{rej}}{Q_{sup}} = 1 - \dfrac{T_3}{T_1}$
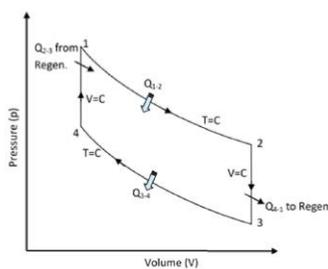
P-V DIAGRAM
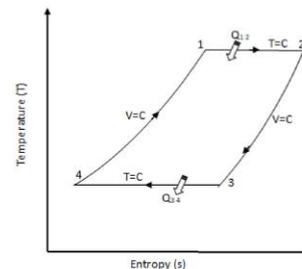
T-S DIAGRAM

It is observed from the above expression that efficiency of the Stirling cycle is the same as that of Carnot cycle.

So, referring to the PV diagram and TS diagram of the Stirling engine

Heat supplied: $Q_{sup} = Q_{1-2} = RT_1 \ln \dfrac{v_2}{v_1}$

Heat rejected: $Q_{rej} = Q_{3-4} = RT_3 \ln \dfrac{v_3}{v_4}$

From p-v diagram, $\dfrac{v_2}{v_1} = \dfrac{v_3}{v_4}$

$\eta = 1 - \dfrac{Q_{rej}}{Q_{sup}} = 1 - \dfrac{T_3}{T_1}$

- Otto cycle consists of <u>two isentropic</u> (reversible adiabatic) and <u>two isochoric</u> (reversible constant volume) processes.
- The cycle was proposed by Frenchman Beau de Rochas in 1876 in Germany.
- Otto cycle is named after Nikolaus A Otto, who built a successful four-stroke engine in 1876 in Germany.
- It is the ideal cycle for spark-ignition reciprocating engines.
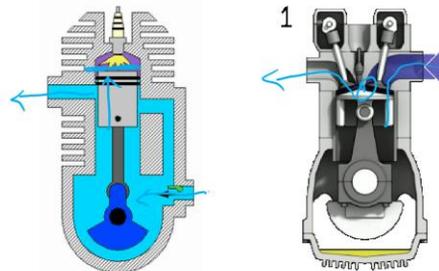
https://energyeducation.ca/encyclopedia/Otto_cycle

24

So, this is the Otto cycle. The Otto Cycle consists of two isentropic and two isochoric processes. Isentropic is a reversible adiabatic process. Two isochoric processes are reversible constant-volume processes. The cycle was proposed by a Frenchman, Beau de Rochas, in 1876 in Germany. The Otto cycle comes from Nikolaus A. Otto, who built a successful four-stroke engine in 1876 in Germany.

It is an ideal cycle for spark ignition. So, if you see here, the inlet of air comes through this. And then, what happens is the air that is there gets compressed and moves in front of the piston. So, once it enters the piston zone, the piston compresses the air. The moment it reaches the top dead center, a spark occurs.

The moment there is a spark, the piston is pushed down, and the exhaust gas is expelled. It is an ideal cycle for spark-ignition reciprocating engines.

So, the PV diagram and the TS diagram are represented like this. So, you will have: 1 to 2 will be compression, 2 to 3 will be heat input, 3 to 4 will be expansion, and 4 to 1 will be heat rejection. So, Q2 to 3 and Q4 to 1 are present.

So, these two process, these two process are constant volume 2 and 3, 1 and 4 are constant volume process. What happens here is reversible adiabatic process happens between 3 to 4 and 2 to 1 or 1 to 2. So, if you draw the corresponding TS diagram, so between 1 to 2 where there is no change in the entropy, the temperature increases

between 1 to 2. Then from 2 to 3, where there is a heat input 2 to 3. So, here what happens, there is a change in S. The S increases with the increase in temperature.

Then from 3 to 4, it is again a constant entropy process. And then from 4 to 1 is a constant volume process. So, otocycle has isentropic compression, constant volume heat addition, it has isentropic expansion, constant volume heat rejection.

Otto 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.

- **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.

In this system, the piston moves upward, decompressing the air-fuel mixture inside the cylinder. The compression happens rapidly and without heat exchange. So, it is pressing in, there is a heat exchange. So, this is an adiabatic cycle. So, the temperature and the pressure of the gas increases significantly. When you try to pressure, the pressure and temperature press, the pressure and temperature goes high. The process stores the energy in the form of increase in internal energy.

So, the constant volume heat addition at the end of the compression increases. The spark ignites because when you ignite it is a combustion. There is a propagation of explosive energy moving front. The spark ignites the fuel air mixture. The combustion occurs quickly.

Instantly it attacks, it does it. The heat is added at a constant volume because the piston is momentarily at the top dead center. This sudden addition of energy causes the pressure

and temperature to the gas to rise sharply. So constant volume when it is exactly there, here close by. First is going here, then you are going very close to TDS, so there you are trying to talk about.

The combustion occurs quickly. When it is compressed, there is a spark plug immediately. The heat is added at constant volume because the piston is momentarily at the top most center. This sudden addition of energy will try to next stage expand.

Otto Cycle

- **Isentropic Expansion (Power Stroke) (3–4):**

  The high-pressure gas now pushes the piston down, doing useful **work on the crankshaft**. This expansion occurs **without any heat exchange**, so it is also adiabatic. As the gas expands, its temperature and pressure drop. This is the **power stroke** of the engine.

- **Constant Volume Heat Rejection (4–1):**

  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 intake stroke.

So, isentropic expansion happens. The pressure gas now pushes the piston down doing useful work on the crankshaft. So, now this one when it is pushed down the crankshaft rotates and then it starts the cranking. So, there is an output. This expansion occurs without any heat exchange. This expansion occurs without any heat exchange, so it is also adiabatic in nature.

As the gas expands, its temperature and pressure drops. This is called the power stroke, isentropic 3 to 4, isentropic 3 to 4 is a power stroke. And then once the piston reaches the bottom dead center the exhaust valve opens and the gas is cooled the gas is cooled at constant volume. exhaust gas once it goes to the top so you see inlet coming in compression the the ignition happen then there is this valve opening so once the piston reaches the top dead center the exhaust valve opens and the gas is cooled at constant

volume rejecting heat to the surrounding so the exhaust gas whatever comes in your two-wheeler if you try to keep very close it to the exhaust pipe it is it has a heat This reduces the pressure and temperature of the gas, completing the cycle and preparing it for the next cycle. This portion is called as power stroke, which is there in the in the Otto cycle. So 3 to 4 is a power stroke. 3 to 4 is a power stroke.

Otto Cycle Efficiency

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

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

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

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

$\Rightarrow \eta = 1 - \dfrac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$

As the processes 1-2 and 3-4 are isentropic;

$\dfrac{T_2}{T_1} = \left(\dfrac{V_1}{V_2}\right)^{\gamma-1}$ and $\dfrac{T_3}{T_4} = \left(\dfrac{V_4}{V_3}\right)^{\gamma-1}$

As $V_3 = V_2$ and $V_4 = V_1$; $\dfrac{V_1}{V_2} = \dfrac{V_4}{V_3}$

$\Rightarrow \dfrac{T_2}{T_1} = \dfrac{T_3}{T_4}$ or $\dfrac{T_4}{T_1} = \dfrac{T_3}{T_2}$

$\Rightarrow \eta_{Otto} = 1 - \dfrac{T_1}{T_2}$

As the process 1-2 is isentropic;

$\dfrac{T_1}{T_2} = \left(\dfrac{V_2}{V_1}\right)^{\gamma-1} = \left(\dfrac{1}{r_c}\right)^{\gamma-1} = \dfrac{1}{r_c^{\gamma-1}}$ where the compression ratio is $r_c = V_1/V_2$

$\therefore \eta_{Otto} = 1 - \dfrac{1}{r_c^{\gamma-1}}$

28

So, when we have trying to refer back to PV and TS diagram.

As the process 1 to 2 is isentropic in nature, you get this formula. And finally, the efficiency which is followed is 1 minus 1 by rc gamma minus 1. Where rc is nothing but the compression ratio. What is the compression ratio? V1 by V2. So, we have changed this RC.

Otto Cycle

Mean Effective Pressure (p_m or mep)

$$p_m (or\ mep) = \frac{W_{net}}{V_s} = \frac{Q_{net}}{V_1 - V_2} = \frac{Q_{sup} - Q_{rej}}{V_1\left[1 - (V_2/V_1)\right]}$$
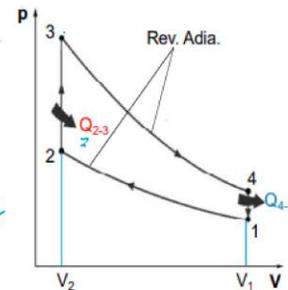
Where

$$Q_{sup} = Q_{2-3} = mC_v(T_3 - T_2)$$

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

$$V_1 = \frac{mRT_1}{P_1} \quad and \quad \frac{V_2}{V_1} = \frac{1}{r_c}$$

$\gamma_2 = r_c$

$\frac{V_2}{V_1} = \frac{1}{r_c}$

$PV = mRT$

P-V DIAGRAM

So, the mean effective pressure Pm.

$$p_m (or\ mep) = \frac{W_{net}}{V_s} = \frac{Q_{net}}{V_1 - V_2} = \frac{Q_{sup} - Q_{rej}}{V_1\left[1 - (V_2/V_1)\right]}$$

Where

$$Q_{sup} = Q_{2-3} = mC_v(T_3 - T_2)$$

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

$$V_1 = \frac{mRT_1}{P_1} \quad and \quad \frac{V_2}{V_1} = \frac{1}{r_c}$$

Otto Cycle

Upon substitution

$$P_m = \frac{mC_v(T_3 - T_2) - mC_v(T_4 - T_1)}{(mRT_1/p_1)\left[1 - (1/r_c)\right]}$$

$$P_m = \frac{C_v(T_3 - T_2) - C_v(T_4 - T_1)}{\left[\frac{C_v(\gamma-1)T_1}{R}/p_1\right](r_c - 1)/r_c}$$

$$P_m = \frac{p_1 r_c \left\{\left[T_2((T_3/T_2) - 1)\right] - T_1\left[(T_4/T_1) - 1\right]\right\}}{T_1(\gamma - 1)(r_c - 1)} \quad \text{------(2)}$$

As the processes 1-2 and 3-4 are isentropic,

and $V_3 = V_2$, $V_4 = V_1$

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \text{ and } T_2 = T_1 r_c^{\gamma-1}$$

$$\Rightarrow \frac{T_2}{T_1} = \frac{T_3}{T_4}; \text{ or } \frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} \left(= r_c^{\gamma-1} \Rightarrow T_2 = T_1 r_c^{\gamma-1}\right)$$

$$R = C_p - C_v \Rightarrow \frac{R}{C_v} = \frac{C_p}{C_v} - 1 = \gamma - 1$$
$$\therefore R = C_v(\gamma - 1)$$

As the process 2-3 is isochoric;

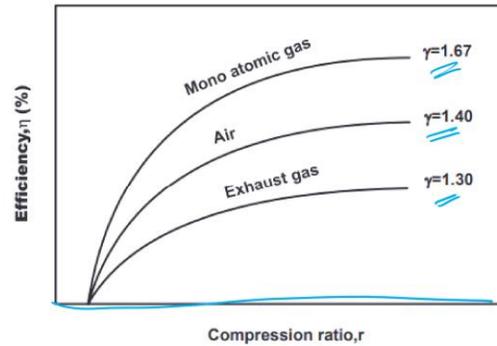$$\frac{p_2}{T_2} = \frac{p_3}{T_3} \Rightarrow \frac{T_3}{T_2} = \frac{p_3}{p_2} = \alpha \text{ (Explosion Ratio)}$$

On substitution into Eqn. (2),

$$P_m = \frac{p_1 r_c \left\{\left[T_1 r_c^{\gamma-1}(\alpha - 1)\right] - T_1[\alpha - 1]\right\}}{T_1(\gamma - 1)(r_c - 1)}$$

$$P_m = \frac{p_1 r_c (\alpha - 1)(r_c^{\gamma-1} - 1)}{(\gamma - 1)(r_c - 1)}$$

30

Upon substituting

So, finally, Pm, which is there, which is nothing but the mean effective pressure for an Otto cycle, can be obtained by this formula.

Otto Cycle

Effect of CR and γ on efficiency for Otto cycle.

So, when we try to plot the efficiency between compression ratio and efficiency, you can see here the compression ratio for air when gamma equals 1.4. For the exhaust gas, the gamma is equal to 1.3. In a monoatomic gas, the gamma is going to be 1.67. So, this is what people are trying to adjust to get higher efficiency.

So, the effect of the compression ratio (CR) with respect to gamma on the efficiency of an Otto cycle is shown here.

Thank you very much.