Air Standard Cycles and their analysis

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Introduction of Ideal Air Standard Power Cycles

- Operating cycle of an internal combustion engine: intake, compression & combustion, expansion, and exhaust.
Introduction of Ideal Air Standard Power Cycles

- With models for each of these processes, a simulation of a complete engine cycle can be built up which can be analyzed to provide information on engine performance.
- These model cycles are called air standard cycles.

- In an air standard cycles:
  - Certain mass of air operates in a complete thermodynamic cycle
  - Heat is added or rejected with external heat reservoirs
  - All processes in the cycle are reversible.

- The three air standard cycles that model the IC engines are:
  - Otto cycle (approximation of SI engine)
  - Diesel cycle (approximation of CI engine)
  - Limited pressure cycle or Mixed cycle or Dual cycle

Difference between Air Standard Cycles and IC Engine Cycle

(a) P-V diagram of firing spark-ignition engine, \( r_c = 8.4, 3500 \text{ rev/min}, P_i = 0.4 \text{ atm}, P_c = 1 \text{ atm}, \text{ imep. } = 2.9 \text{ atm} \) (b) Constant volume Otto cycle

- Processes of IC engine are not reversible, while air standard cycle processes are reversible.
- In IC engine, air-fuel mixture act as working fluid.
- In IC engine, individual processes are not distinctly identifiable, they overlap.
- In air standard cycle the processes are distinctly identifiable with no overlap.
Difference between Air Standard Cycles and IC Engine Cycle

(a) P-V diagram of firing spark-ignition engine, $r_c = 8.4$, 3500 rev/min, $P_i = 0.4$ atm, $P_e = 1$ atm, imep. = 2.9 atm (b) Constant volume Otto cycle

- In air standard cycle air is considered to be the working fluid, with assumption of ideal gas.
- In internal combustion engine, working fluid's specific heat changes with pressure and temperature,
- In air standard cycle, it is assumed that air's specific heat remain constant.

Otto Cycle

(a) P-V diagram for Otto cycle (b) T-s diagram for Otto cycle

- Otto cycle is the air standard cycle for SI engine.
- This cycle contains two reversible adiabatic (constant entropy) processes and two reversible isochors (constant volume) processes.

Mechanical cycle corresponding to the Ideal processes of Otto cycle
Otto Cycle

- **Process 1-2 - Intake:**
  - Inlet valve is open,
  - Piston moves to bottom, admitting fuel-air mixture into the cylinder at constant pressure.

- **Process 2-3 - Compression:**
  - Both valves are closed
  - Piston compresses the combustible mixture to the minimum volume.

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Otto Cycle

- **Process 3-4 – Combustion:**
  - Mixture is then ignited by spark
  - Combustion takes place accompanied by an increase in temperature and pressure.

- **Process 4-5 – Expansion:**
  - Products of combustion do work on piston which moves to bottom.
  - Pressure and temperature of the gas decreases.
Otto Cycle

- **Process 5-6 – Blow down:**
  - Exhaust valve opens
  - Pressure drops to the initial pressure.
- **Process 6-1 – Exhaust:** Exhaust valve remains open
  - Piston moves upwards to expel combustion products from the cylinder at constant pressure.

![P-V diagram for Otto cycle](image)

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**Otto Cycle**

**Assumptions**

- Working fluid is an ideal gas assumed to be air following $PV = mRT$.
- There is no change in the mass of working fluid during the cycle.
- All processes are reversible.
- Heat is assumed to supplied from constant high temperature source and not from the chemical reaction during the cycle.
- Heat loss from system to surrounding are neglected other than exhaust.
- Specific heat constants of working cycle are assumed to be constant during the entire cycle.
- $C_v = 0.718\text{kJ/kg-K}$, $\gamma = C_p/C_v = 1.4$, $R = 0.287\text{kJ/kg-K}$
Otto Cycle

- Process 1-2: Air is compressed reversibly and adiabatically
- Process 2-3: Heat is added to air reversibly at constant volume process
- Process 3-4: Work is done by air reversibly and adiabatically on the piston
- Process 4-1: Heat is rejected reversibly at constant volume and the system comes back to initial state
- If \( m \) is the fixed mass of air undergoing the cycle of operation then,
  
  - Heat supplied: \( Q_1 = Q_{2-3} = mc_v(T_3 - T_2) \)
  - Heat rejected: \( Q_2 = Q_{3-4} = mc_v(T_4 - T_3) \)
  - Efficiency can be given as:
    \[
    \eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_3 - T_2)}{mc_v(T_4 - T_3)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}
    \]

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Otto Cycle

- From process 1-2:
  
  \[
  \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{y-1}
  \]
- From process 3-4:
  
  \[
  \frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{y-1} = \left(\frac{v_1}{v_2}\right)^{y-1}
  \]
- From above equations,
  
  \[
  \frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{y-1}
  \]
- Using above expressions, efficiency can be expressed as:
  
  \[
  \eta = 1 - \left(\frac{v_2}{v_1}\right)^{y-1} = 1 - \frac{1}{r_c^{y-1}}
  \]

where \( r_c \) is the compression ratio, \( r_c = v_1/v_2 \)

Continued..
Otto Cycle

- Thus, efficiency of air standard Otto cycle is a function of compression ratio only.
- Higher the compression ratio, higher is the efficiency.
- Compression ratio cannot be increased beyond a certain limit because of detonation which is a noisy and destructive combustion phenomenon.

Diesel Cycle

(a) An ideal CI engine (b) p-v diagram for ideal diesel cycle

- Diesel cycle is the air standard cycle for CI engine.
- Limitation of compression ratio can be overcome by compressing air alone, instead of fuel-air mixture.
- Then injecting the fuel into the cylinder in spray form when combustion is desired.
Diezel Cycle

(a) An ideal CI engine (b) p-v diagram for ideal diesel cycle

- Temperature of air after compression is high enough so that fuel sprayed into the hot air burns spontaneously.
- **Diesel cycle**: two reversible adiabatic, one reversible isobar and one reversible isochors process.

Mechanical cycle corresponding to the Ideal processes of Diesel cycle **Continued..**

### Diesel Cycle

- **Process 1-2 – Intake:**
  - Air valve is open.
  - Piston moves out admitting air into the cylinder at constant pressure

- **Process 2-3 – Compression:**
  - Air is then compressed by the piston to the minimum volume with all valve closed

P-V diagram for Diesel cycle
Diesel Cycle

➢ Process 3-4 – Fuel injection and combustion:
  • Fuel valve is open and fuel is sprayed over the hot air
  • Combustion takes place at constant pressure

➢ Process 4-5 – Expansion:
  • Combustion products expand, do work on the piston which moves out to the maximum volume

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P-V diagram for Diesel cycle
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Continued...

Diesel Cycle

➢ Process 5-6 – Blow-down:
  • Exhaust valve opens, and pressure drops to initial pressure

➢ Process 6-1 – Exhaust:
  • Exhaust valve opens
  • Piston moves upwards, drives away combustion products from the cylinder at constant pressure.

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P-V diagram for Diesel cycle
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Continued..
Diesel Cycle

(a) P-V diagram for Diesel cycle (b) T-s diagram for Diesel cycle

- Process 1-2: Air is compressed reversibly and adiabatically
- Process 2-3: Heat is added to air reversibly at constant pressure
- Process 3-4: Work is done by air reversibly and adiabatically
- Process 4-1: Heat is rejected reversibly at constant volume and cycle repeats

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Diesel Cycle

(a) P-V diagram for Diesel cycle (b) T-s diagram for Diesel cycle

- If \( m \) is the fixed mass of air undergoing the cycle of operation then,
- Heat supplied \( Q_1 = Q_{2-3} = mc_p(T_3 - T_2) \)
- Heat rejected \( Q_2 = Q_{4-1} = mc_v(T_4 - T_1) \)
- Efficiency can be given as:

\[
\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_3 - T_2)}{mc_p(T_4 - T_1)} = 1 - \frac{T_4 - T_1}{\gamma(T_3 - T_2)}
\]
Diesel Cycle

- Compression ratio
  \[ r_c = \frac{v_1}{v_2} \]

- Cut-off ratio
  \[ r_k = \frac{v_3}{v_2} \]

- Expansion ratio
  \[ r_s = \frac{v_4}{v_3} \] and \[ r_c = r_e r_k \]

- From Process 3-4
  \[ \frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma - 1} = \frac{1}{r_k r_c^{\gamma - 1}} \Rightarrow T_4 = T_3^{\frac{r_k r_c^{\gamma - 1}}{r_k^{\gamma - 1}}} \]

- From process 2-3
  \[ \frac{T_2}{T_3} = \frac{p_2 v_2}{p_3 v_3} = \frac{v_2}{v_3} = \frac{1}{r_k} \Rightarrow T_2 = T_3^{\frac{1}{r_k}} \]

Continued...

### Diesel Cycle

- From process 1-2
  \[ \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma - 1} = \frac{1}{r_c r_k^{\gamma - 1}} \Rightarrow T_1 = T_2^{\frac{1}{r_c r_k^{\gamma - 1}}} = T_3^{\frac{1}{r_k r_c^{\gamma - 1}}} \]

- With help of above equations,
  \[ \eta = 1 - \frac{1}{r_k} \left(1 - \frac{r_k^{\gamma - 1}}{r_c^{\gamma - 1} r_k r_c^{\gamma - 1}}\right) \]

- As \( r_k > 1 \) the \( \frac{1}{r_k} \left(1 - \frac{r_k^{\gamma - 1}}{r_k^{\gamma - 1} r_k}\right) \) is also greater than unity.

- Therefore the efficiency of Diesel cycle is less than Otto cycle for same compression ratio.

Continued...
Limited Pressure Cycle, Mixed Cycle or Dual Cycle

(a) P-V diagram for Dual cycle  (b) T-s diagram for Dual cycle

- Air standard diesel cycle does not simulate exactly the p-v variation in an actual CI engine, where the fuel injection is started before the end of compression stroke.
- A closer approximation to CI engine is Dual cycle, in which some part of the heat is added at constant volume and remaining at constant pressure.
- Dual cycle contains two reversible adiabatic, one reversible isobar and two reversible isochors process.

Dual Cycle

- Process 1-2: Air is compressed reversibly and adiabatically.
- Process 2-3 Heat is added to air reversibly at constant volume 2-3
- Process 3-4: Heat addition to air at constant pressure
- Process 4-5: Work is done by air reversibly and adiabatically.
- Process 5-1: Heat is rejected reversibly at constant volume process 5-1 and cycle repeats.

T-s diagram for Dual cycle
Dual Cycle

- If $m$ is the fixed mass of air undergoing the cycle of operation then.
  
  Heat supplied $Q_1 = mc_v(T_3 - T_2) + mc_p(T_4 - T_3)$.
  
  Heat rejected $Q_2 = mc_v(T_5 - T_1)$
  
  Efficiency can be given as;
  
  \[
  \eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_5 - T_1)}{mc_v(T_3 - T_2) + mc_p(T_4 - T_3)}
  \]
  
  \[
  = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}
  \]
  
- Compression ratio $r_c = \frac{v_1}{v_2}$ Cut-off ratio $r_k = \frac{v_4}{v_3}$
  
- Expansion ratio $r_e = \frac{v_5}{v_4}$ and Constant volume pressure ratio $r_p = \frac{p_3}{p_2}$
  
  \[
  r_c = r_e r_k
  \]

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Continued...

Dual Cycle

- From process 3-4,
  
  \[
  r_k = \frac{v_4}{v_3} = \frac{T_4 p_3}{T_3 p_3} = \frac{T_4}{T_3} \Rightarrow T_3 = T_4 \frac{1}{r_k}
  \]
  
- From process 2-3,
  
  \[
  \frac{p_3 v_3}{T_2} = \frac{p_2 v_3}{T_1} \Rightarrow T_2 = T_1 \frac{p_2}{p_1} = \frac{T_1}{r_p r_s}
  \]
  
- From process 1-2,
  
  \[
  \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{-\gamma} = \gamma^{-\gamma-1} \Rightarrow T_1 = T_2 \frac{1}{r_p r_s r_e^{-\gamma-1}}
  \]
  
- From process 4-5,
  
  \[
  \frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{-\gamma} = \gamma^{-\gamma-1} \Rightarrow T_5 = T_4 \frac{1}{r_e r^{\gamma-1}}
  \]
  
- With help of above equations,
  
  \[
  \eta = 1 - \frac{1}{r_e r^{-1} r_p r - 1 + \gamma r_p (r_k - 1)}
  \]

(a) P-V diagram for Dual cycle

(b) T-s diagram for Dual cycle
Comparison of Otto, Diesel and Dual Cycles

For same compression ratio

- **Otto cycle**: 1-2-6-5, **Diesel cycle**: 1-2-7-5 and **Dual cycle**: 1-2-3-4-5
- For the same Q2, higher the Q1, higher is the cycle efficiency.
- T-S diagram: area under 2-6 represent Q1 for Otto cycle, area under 2-7 represent Q1 for Diesel cycle and area under 2-3-4 represent Q1 for the Dual cycle.
- From the diagram for same compression ratio;
  \[ \eta_{otto} > \eta_{dual} > \eta_{diesel} \]

For same maximum pressure and temperature

- **Otto cycle**: 1-6-4-5, **Diesel cycle**: 1-7-4-5 & **Dual cycle**: 1-2-3-4-5
- T-S diagram: Q1 represented by area under 6-4 for Otto cycle, by area under 7-4 for diesel cycle and area under 2-3-4 for the Dual cycle. Q2 being the same for all.
- For same maximum pressure and temperature,
  \[ \eta_{diesel} > \eta_{dual} > \eta_{otto} \]
Deviation of Actual Cycle from Air Standard Cycle

The actual cycle deviates from the air standard cycles for following factors

✧ Heat transfer

➢ Heat transfer from the burned gases have significant effect on the P-V line.
➢ Due to heat transfer during combustion, pressure at the end of combustion in the real cycle will be lower.
➢ During expansion, heat transfer will cause the gas pressure in the real cycle to fall below an isentropic expansion line as the volume increases.
➢ A decrease in efficiency results from these heat losses.

Deviation of Actual Cycle from Air Standard Cycle

✧ Finite Combustion time

➢ Combustion typically starts 10° to 40° CAD before TDC, is half complete at about 10° after TDC, and is essentially complete 30° to 40° after TDC.
➢ Peak pressure occurs at about 15° after TDC. In diesel engine, the burning process starts shortly before TDC.
➢ Pressure rises rapidly to a peak at about 5" to 10" after TDC since the initial rate of burning is fast.
➢ However, final stages of burning are much slower, and combustion continues until 40° to 50° after TDC.
➢ Thus, peak pressure in the engine is substantially below the fuel-air cycle peak pressure value, because combustion continues until well after TDC, when the cylinder volume is much greater than the clearance volume.
➢ After peak pressure, expansion stroke pressures in the engine are higher than fuel-air cycle values in the absence of other loss mechanisms, because less work is extracted from the cylinder gases.
Deviation of Actual Cycle from Air Standard Cycle

- **Exhaust blow down loss**
  - In real engine, exhaust valve is opened at about 60° before BDC to reduce the pressure during the first part of exhaust stroke in four-stroke engines and to allow time for scavenging in two stroke engines.
  - Gas pressure at the end of expansion stroke is therefore reduced below the isentropic line.
  - A decrease in expansion-stroke work transfer results.

- **Crevise effect and leakage**
  - As cylinder pressure increases, gas flows into crevices such as the regions between the piston, piston rings, and cylinder wall.
  - These crevice regions can comprise a few percent of the clearance volume.
  - This flow in crevices reduces mass in the volume above the piston crown, and is cooled by heat transfer to the crevice walls.
  - In premixed charge engines, some of this gas is unburned and some of it will not burn.
  - Though much of this gas returns to the cylinder later in expansion stroke, a fraction from behind and between the piston rings, flows into the crankcase.

- **Incomplete combustion**
  - Combustion of the cylinder charge is incomplete; exhaust gases contain combustible species.
  - In SI engines, hydrocarbon emissions from a warmed-up engine are 2-3% of fuel mass under normal operating conditions.
  - CO and H₂ in the exhaust contain an additional 1-2% or more of the fuel energy, even with excess air present.
  - Hence, chemical energy of the fuel which is released in the actual engine is about 5% less than the chemical energy of the fuel inducted.
  - In diesel engines, combustion inefficiency is usually less, about 1-2%, so this effect is smaller.
Thanks