Internal Combustion Engines

"An Engine is a device that converts heat energy into mechanical energy to do work"

The heat energy is supplied through combustion of fuel

$$\text{Fuel } (C_8H_{15}) + \text{Air } (O_2\ ,\ N_2) \Longrightarrow CO_2 + H_20 + N_2 + \text{Heat}$$

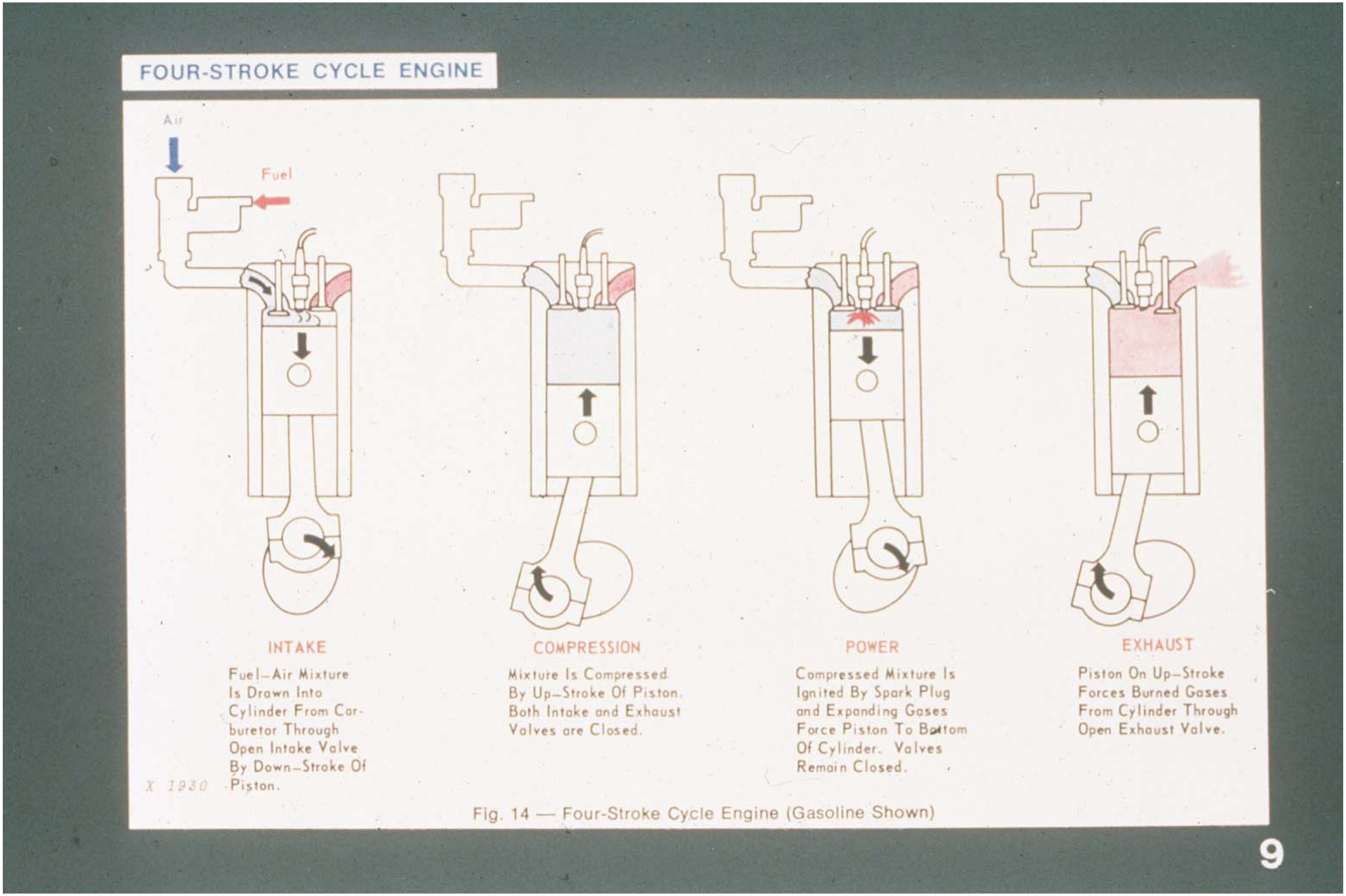
$$\text{Fuel } (C_8H_{15}) + \text{Air } (O_2\ ,\ N_2) \Longrightarrow CO_2 + H_20 + N_2 + \text{Heat} + CO + H_20 + N0_x$$

Air Fuel & Combustion

- Fuel
  - Fuel and air must be mixed
    - Fuel must be vaporized
  - Combustion Rate
    - Temperature
    - Vaporization
  - Controlled Rate of Combustion
    - Compression Ratio
    - Injection/Spark Timing
    - Air/Fuel Ratio
- Pre-mix Flame / Diffusion Flame
    - Ignition Delay

Four Stroke Engine

- Intake Stroke
  - Piston TDC ⇒ Piston BDC
    - Intake Valve Open (10^{o} before TDC)
    - Intake Valve Closes (50^{o} after BDC)
- Compression Stroke
  - Piston BDC ⇒ Piston TDC
    - All Valves Closed
- Power Stroke (Ignition/Injection at TDC)
  - Piston TDC ⇒ Piston BDC
- Exhaust Stroke
  - Piston BDC ⇒ Piston TDC
    - Exhaust Valve Open (50^{o} before BDC)
    - Exhaust Valve Closes (10^{o} after TDC)



FOUR-STROKE CYCLE ENGINE

INTAKE

Fuel–Air Mixture Is Drawn Into Cylinder From Carburetor Through Open Intake Valve By Down–Stroke Of Piston.

COMPRESSION

Mixture Is Compressed By Up–Stroke Of Piston. Both Intake and Exhaust Valves are Closed.

POWER

Compressed Mixture Is Ignited By Spark Plug and Expanding Gases Force Piston To Bottom Of Cylinder. Valves Remain Closed.

EXHAUST

Piston On Up–Stroke Forces Burned Gases From Cylinder Through Open Exhaust Valve.

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Fig. 14 — Four-Stroke Cycle Engine (Gasoline Shown)

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Two Stroke Engine (Crankcase Scavenging)

CRANKCASE INTAKE

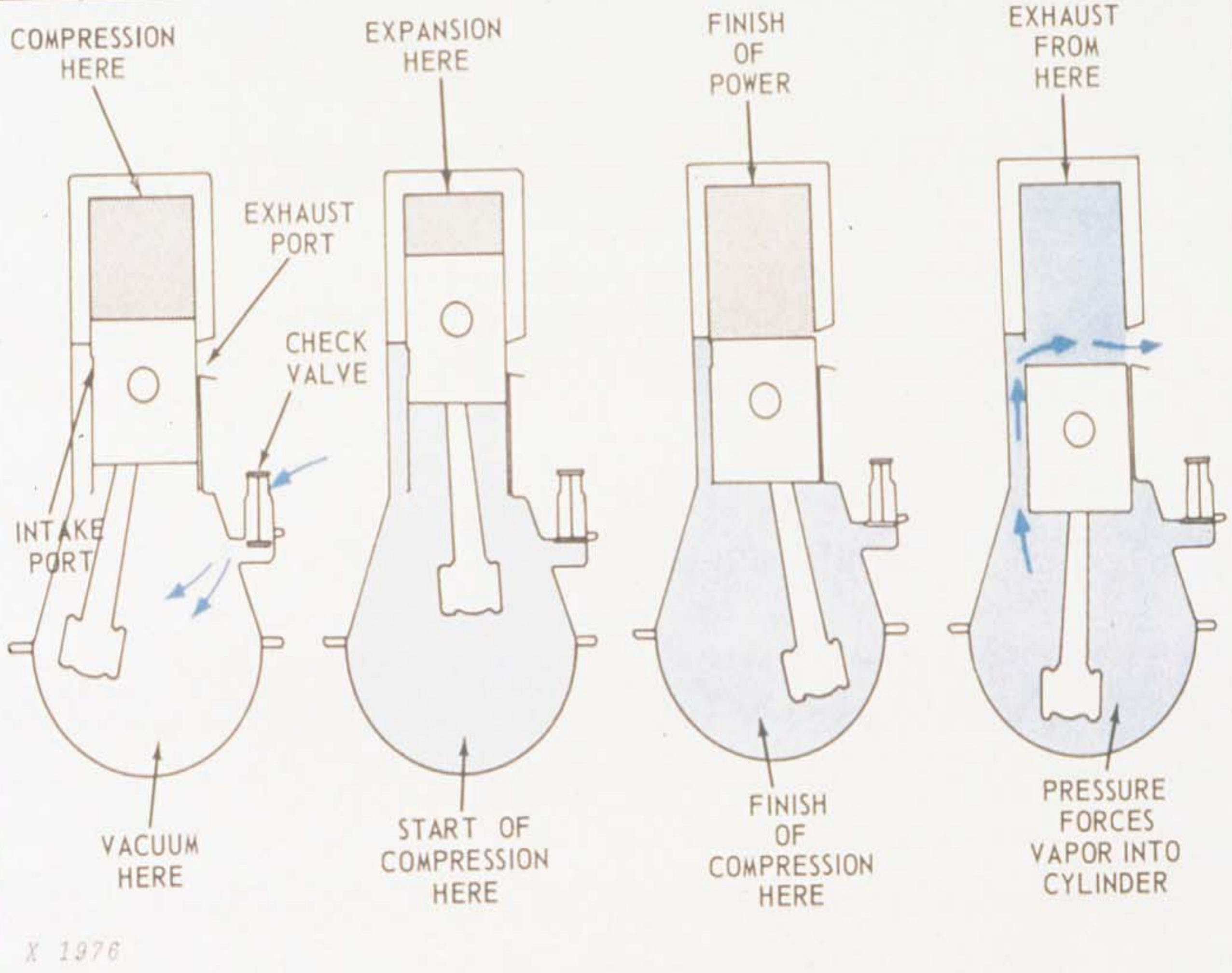


Fig. 19 — Crankcase Intake System

Air Fuel & Combustion

- Air
  - Air will compress

$$pV=MRT$$

p = Pressure (kPa, psi), V= volume (m3, ft3), M=Mass (kg, lb), T= Absolute Temperature (K, R)

R=specific gas constant (8.314/molecular weight [metric], 10.72/molecular weight [English])

- Constant Mass of air
  - Decrease in Volume ⇨ Increase in Temperature
  - Increase in Pressure

  - Addition of Energy ⇨ Increase in Temperature
  - Increase in Pressure

Gas Laws

Ideal Gas Equation

$$pV=MRT$$

p = Pressure (kPa, psi), V= volume (m3, ft3), M=Mass (kg, lb), T= Absolute Temperature (K, R)
R=specific gas constant (8.314/molecular weight [metric], 10.72/molecular weight [English])

- Constant Volume

  $p_b/p_a = T_b/T_a$

  $Q/M = C_v *(T_b - T_a)$

- Constant Pressure

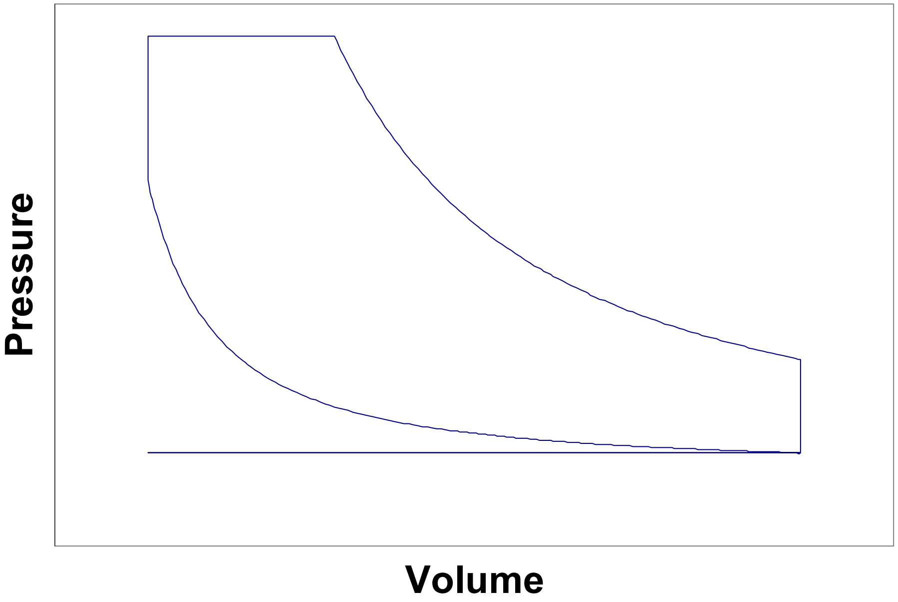
  $V_b/V_a = T_b/T_a$

  $Q/M = C_p *(T_b - T_a)$

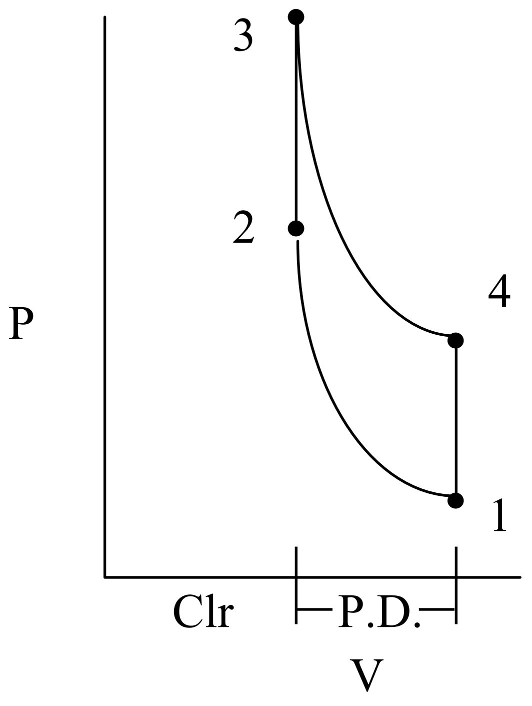
- Adiabatic Expansion/Compression

  $p_b/p_a = [V_a/V_b]^k = [T_b/T_a]^{k/(k-1)}$

  $T_b/T_a = [V_a/V_b]^{(k-1)} = [p_b/p_a]^{(k-1)/k}$

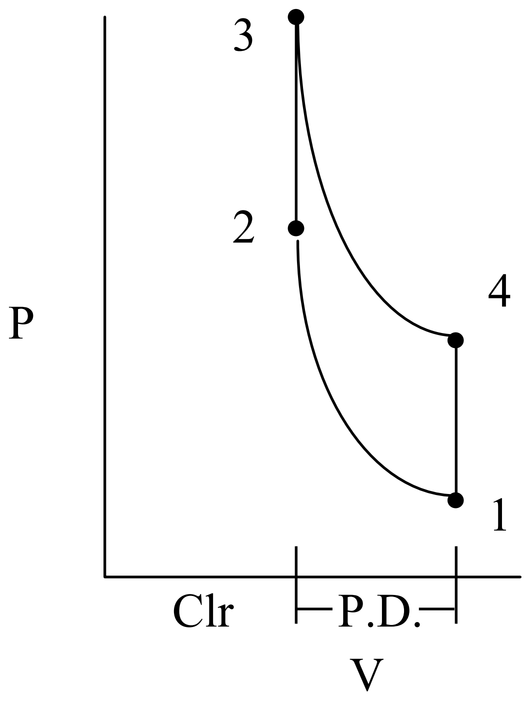


Ideal Otto Cycle Assumptions



- The piston has zero friction in the cylinder
- Air is the working fluid
- No heat transfer through the cylinder walls
- The crank starts at the bottom of the stroke under conditions of P_1, V_1, and T_1
- Adiabatic compression from 1-2
- Adiabatic expansion from 3-4
- Constant-volume addition of heat from 2-3
- Constant-volume rejection of heat from 4-1
- The working fluid (air) is treated as a perfect gas with constant specific heats
- All thermodynamic processes are assumed ideal

Ideal Otto Cycle Efficiency



- Heat added at constant volume during the cycle is:

  $Q_{in} = M\, c_v\, (T_3 - T_2)$

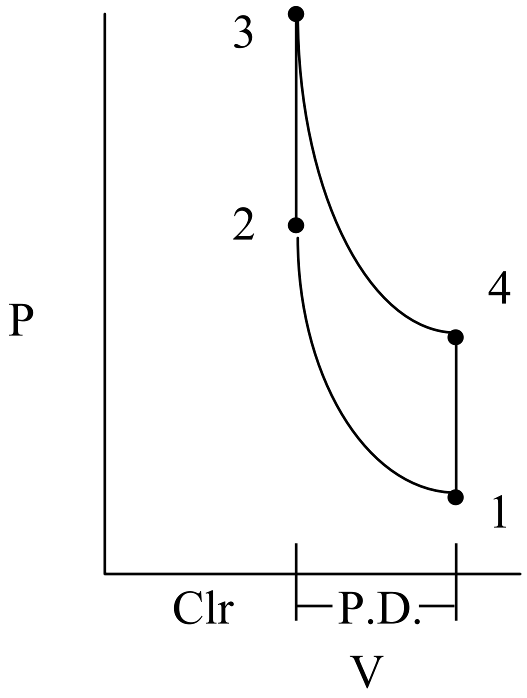
- Heat rejected at constant volume during the cycle is:

  $Q_{in} = M\, c_v\, (T_4 - T_1)$

$$e = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{T_1}{T_2} = 1 - \left[\frac{v_2}{v_1}\right]^{k-1} = 1 - \frac{1}{r^{k\text{-}1}} = 1 - \left[\frac{P_1}{P_2}\right]^{(k\text{-}1)/k}$$

Ideal Otto Cycle Work

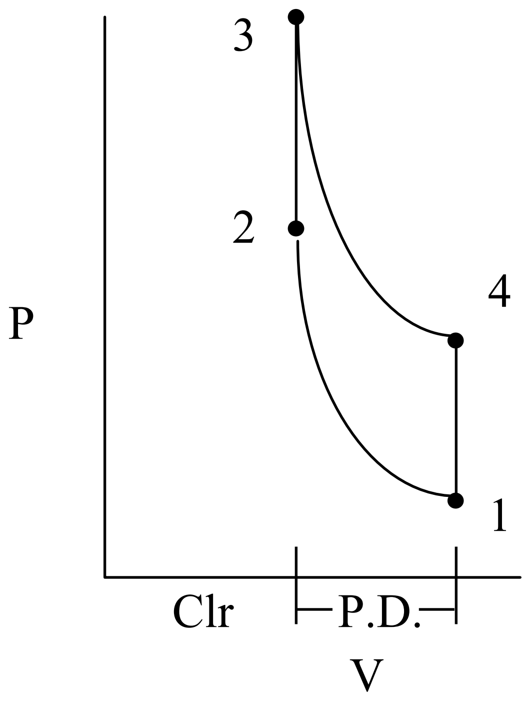
$$W = Q_{in} - Q_{out}$$



$$W = \frac{P_1V_1 - P_2V_2}{k-1} + \frac{P_3V_3 - P_4V_4}{k-1}$$

$$MEP = \frac{\text{Net Work}}{\text{Displacement}}$$

Ideal Otto Cycle Example Problem (p1)



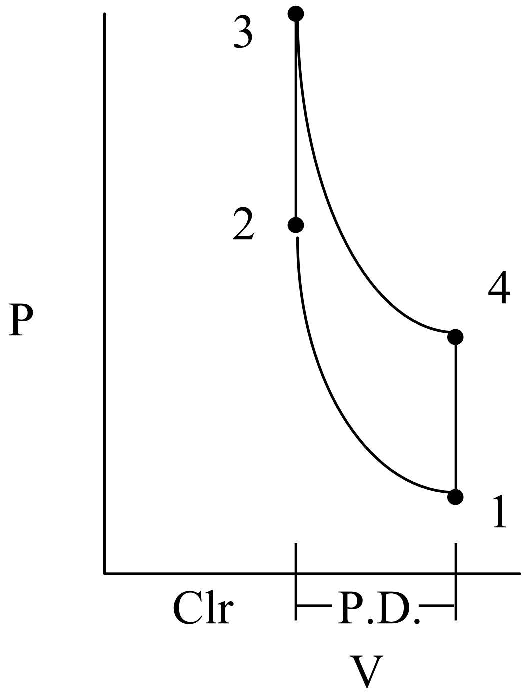
Given

- $P_1 = 96.5$ kPa
- $t_1 = 60°$ C
- $r = 6:1$
- $k = 1.4$
- $Qs = 3021$ kJ/kg

Find

- P's, V's & T's
- Efficiency
- Mean Effective Press (MEP)

Ideal Otto Cycle Example Problem (p2)



First, find the cylinder volume at BDC

From $P_1 V_1 = MRT_1$

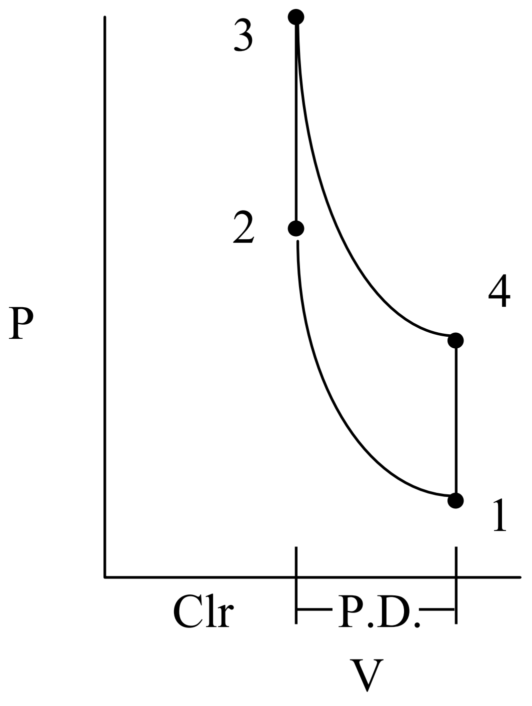
$$V_1 = \frac{MRT_1}{P_1}$$

$$V_1 = \frac{\frac{8314 \text{kNm}}{29 \text{kg}^\circ \text{k}}(60 + 273^\circ)}{96.5 = \frac{\text{kN}}{\text{m}^2}}$$

$$\underline{\underline{V_1 = 0.989 \text{m}^3 / \text{kg}}}$$

& $P_1 =$, $T_1 =$ from prob. statement

Ideal Otto Cycle Example Problem (p3)



For Adiabatic Compression:

$$P_1\ V_1^{k} = P_2 V_2^{k}$$

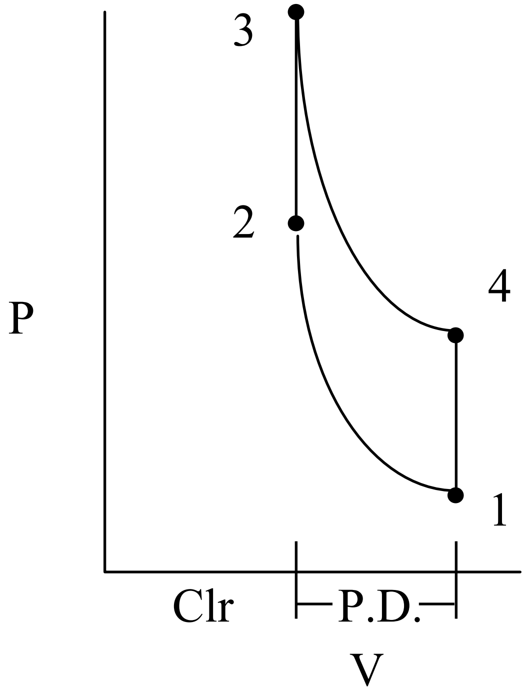
$$P_1 = P_1\left(\frac{V_1}{V_2}\right)^{k} = 96.5\ \frac{kN}{m^2}\left(\frac{6}{1}\right)^{1.4} = \underline{\underline{1186}}\ \frac{kN}{m^2}$$

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = 333(6)^{0.4} = \underline{\underline{682}}^{\circ}\mathrm{K}$$

$$V_2 = \left(\frac{V_1}{r}\right) = \frac{0.989}{6} = \underline{\underline{0.165}}\frac{m^3}{kg}$$

Ideal Otto Cycle Example Problem (p4)

Heat addition 2 → 3 at Constant Volume



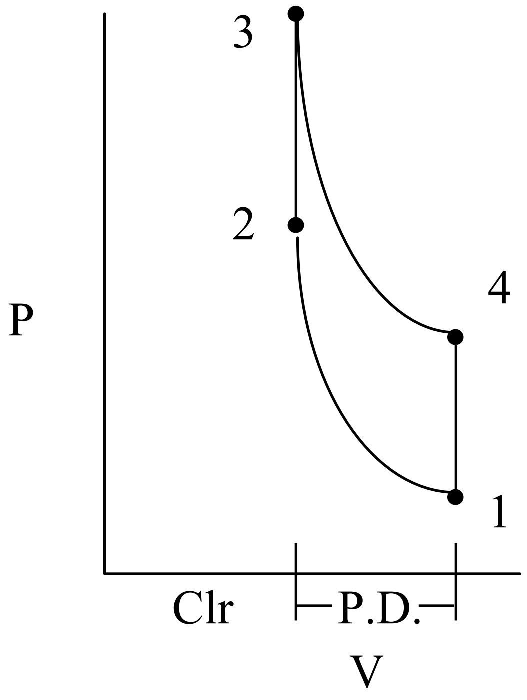
$$Qs_{2\text{-}3} = Mc_v\ (T_3 - T_2)$$

$$T_3 - T_2 = \frac{Qs_{2-3}}{Mc_v} = \frac{3021\,\frac{kJ}{kg}}{1x0.719\,\frac{kJ}{kg°\,k}} = \underline{\underline{4202}}°\,k$$

$$\text{Now}\ \ T_3 = T_2 + (T_3 - T_2)$$

$$\mathbf{T_3} = 682 + 4202 = \underline{\underline{\mathbf{4884}}}°\mathbf{k}$$

Ideal Otto Cycle Example Problem (p5)



Heat addition 2 → 3 at Constant Volume

Also $\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3}$ **but** $V_2 = V_3$

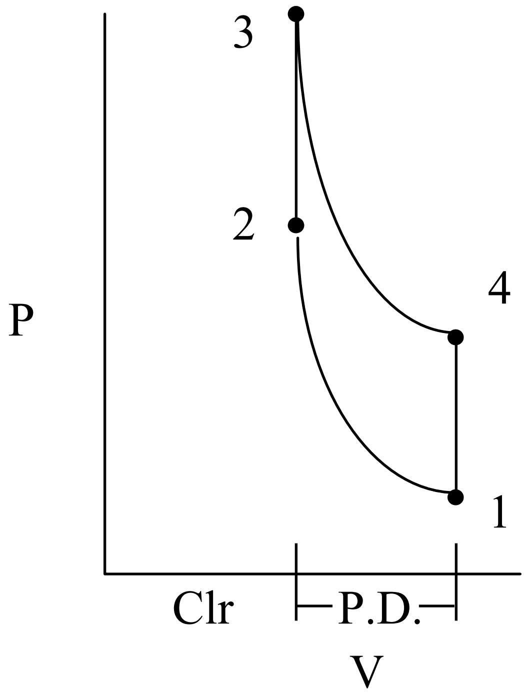
So:

$$P_3 = P_2 \left(\frac{T_3}{T_2} \right) = 1186 \text{ kPa} \left(\frac{4884}{682} \right) = \underline{\mathbf{8494\ kPa}}$$

Since $V_2 = V_3$:

$$V_3 = \underline{\mathbf{0.165 m^3 / kg}}$$

Ideal Otto Cycle Example Problem (p6)



For Adaibatic Expansion 3 → 4:

Since $V_2 = V_3$ & $V_1 = V_4$

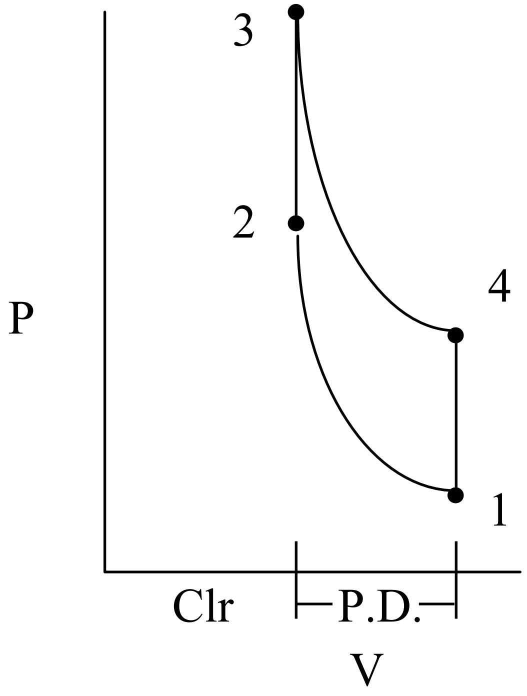
$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{k-1} \qquad \frac{V_1}{V_2} = \frac{V_4}{V_3} = 6$$

$$T_4 = \frac{T_3}{\left(\frac{V_4}{V_3}\right)^{k-1}} = \frac{4884}{(6)^{0.4}} = \underline{\mathbf{2385\ deg\ K}}$$

$$P_4 = \frac{T_3}{\left(\frac{V_4}{V_3}\right)^{k}} = \frac{8494\text{kPa}}{(6)} = \underline{\mathbf{691\ kPa}}$$

and $V_4 = V_1 = \underline{\mathbf{0.989\ m_3 / kg}}$

Ideal Otto Cycle Example Problem (p7)



$$\underline{\text{Heat Rejected } 4 \rightarrow 1 = Q_{R_{4-1}}}$$

$$Q_{R_{4-1}} = Mc_v (T_4 - T_1)$$

$$= 1 \text{ x } 0.719\ (2385 - 333)$$

$$Q_{4-1} = \underline{\mathbf{1475\ kJ / Kg}}$$

Ideal Otto Cycle Example Problem (p8)

$$\text{Net Work} = Q_s - Q_r$$
$$= 3021 - 1475 = \underline{\mathbf{1546\,kJ/kg}}$$

OR:

$$\text{Net Work} = \frac{P_1V_1 - P_2V_2}{k-1} + \frac{P_3V_3 - P_4V_4}{k-1}$$
$$= \frac{96.5(.989) - 1186(.165)}{0.4} + \frac{8494(.165) - 691(.989)}{0.4}$$
$$= -251 + 1796$$
$$= \underline{\mathbf{1545\ kJ/kg}}$$

Ideal Otto Cycle Example Problem (p9)

$$\text{Efficiency} = e = 1 - r^{\frac{1}{k-1}}$$

$$= 1 - \frac{1}{(6)^{0.4}} = \underline{\underline{0.512}}$$

OR:

$$e = \frac{Wk_{out}}{Q_{suppl}} = \frac{1545}{3021} = \underline{0.512}$$

Ideal Otto Cycle Example Problem (p10)

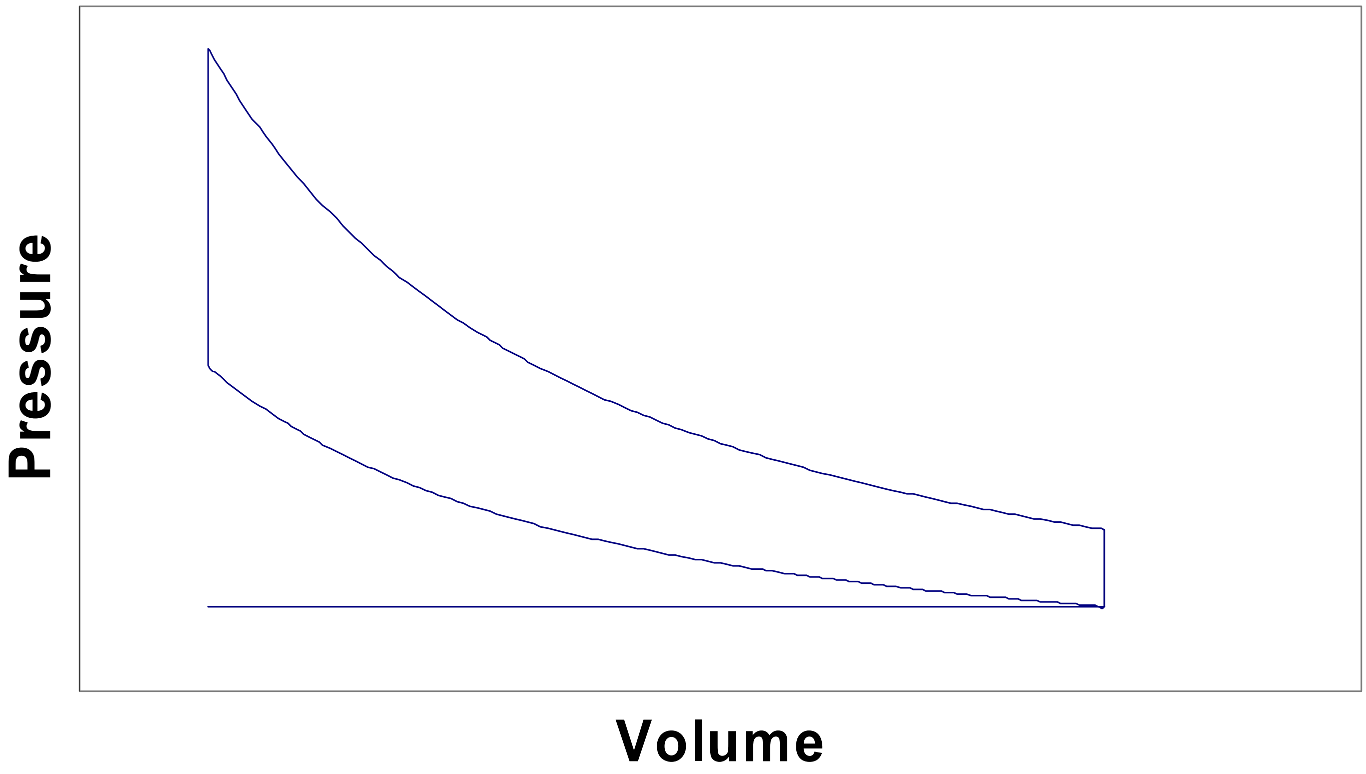
Mean Effective Pressure:

$$MEP = \frac{NetWk}{Displ} = \frac{N \cdot m}{m^3} = \frac{N}{m^2}$$

$$= \frac{1545\ kNm/kg}{0.989\ m^3kg - 0.165m^3/kg}$$

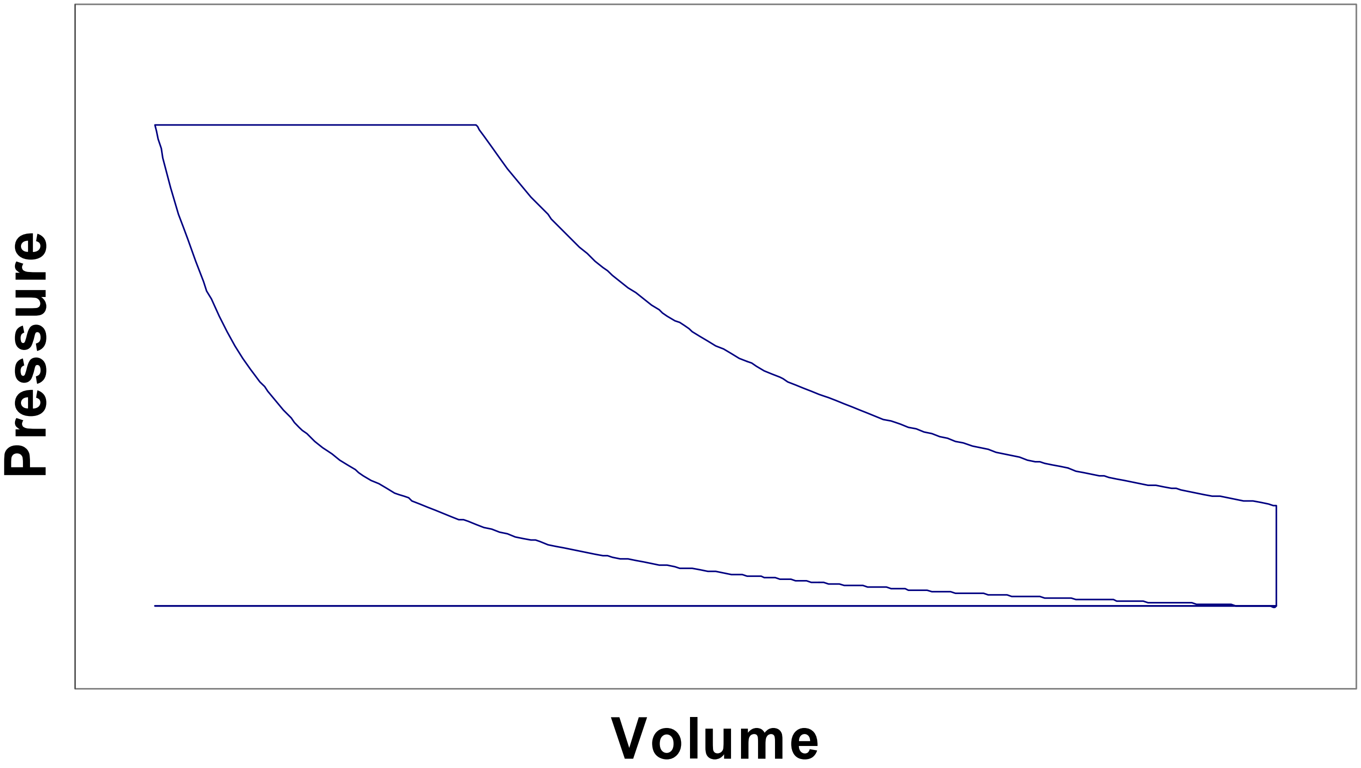
$$= \mathbf{1875\ kN/m^2} = \mathbf{1875\ kPa}$$

Theoretical Otto Cycle (SI)



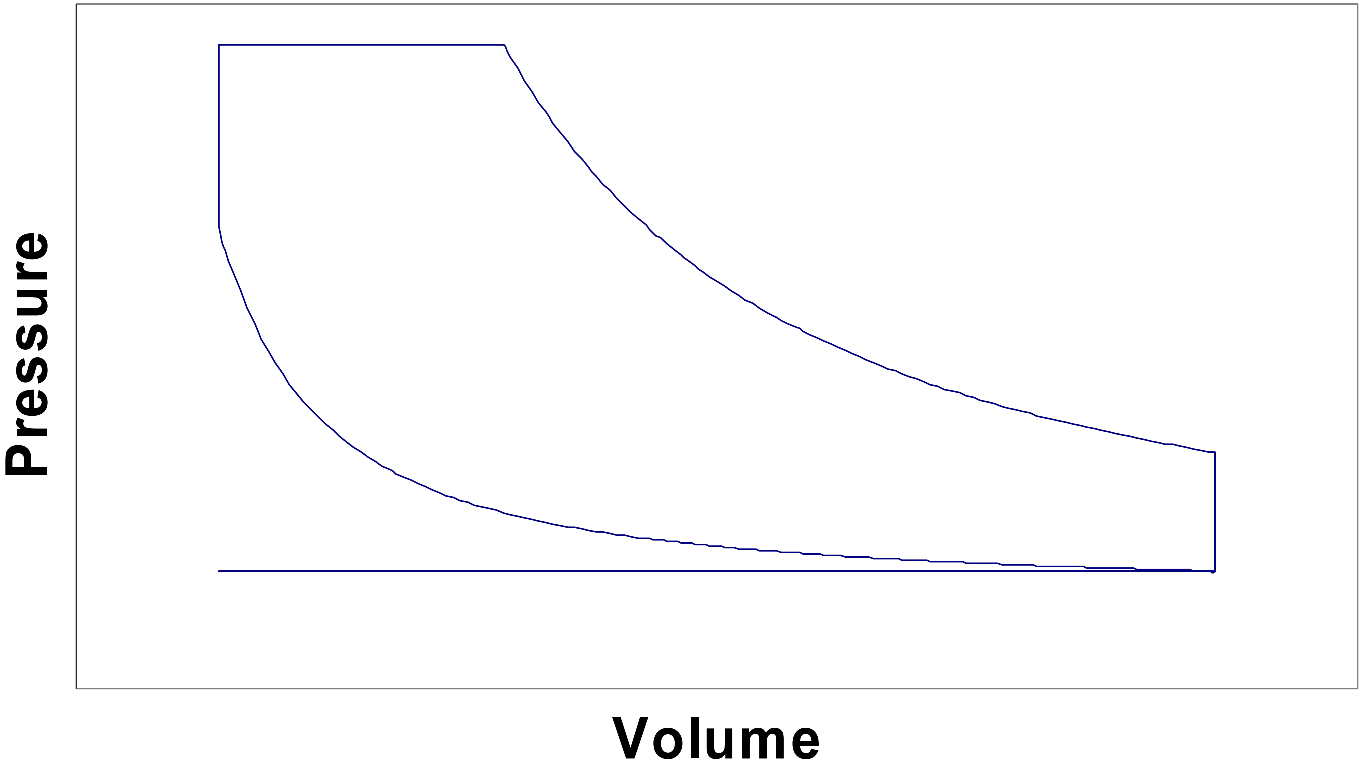
$$\text{Theoretical Efficiency} = 1\text{-}1/r^{(n\text{-}1)}$$

Diesel Cycle (CI)



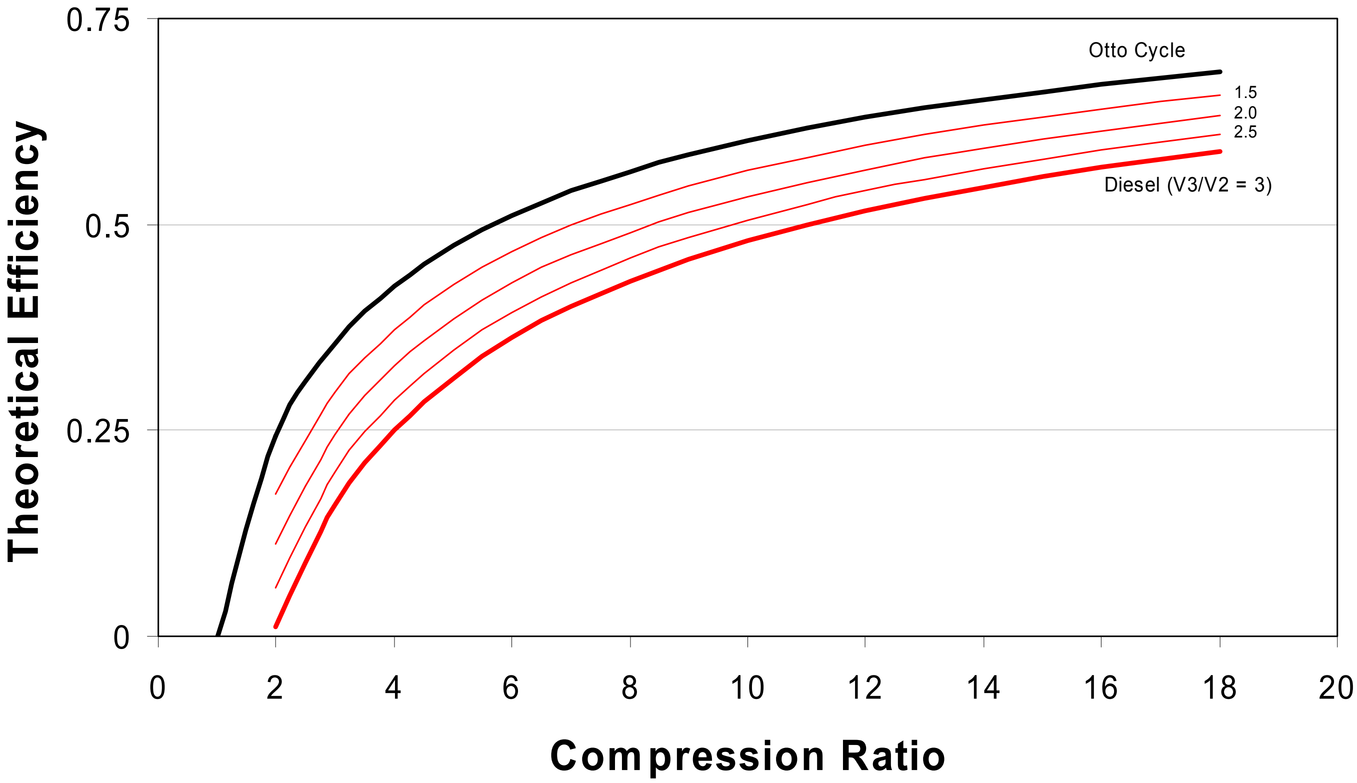
$$\text{Theoretical Efficiency} = 1-[1/r^{(n-1)}]*[(r_{co})^{n} -1] / [n(r_{co} -1)]$$

Dual Cycle



$$\text{Efficiency} = 1-[1/r^{(n-1)}]*\{[B(r_{co}^{\,n}-1)]+n(r_{co}-1)(1-B)\} / [n(r_{co}-1)]$$

Theoretical Cycle Efficiencies



Engine Cycles

- Otto Cycle
  - Theoretical Efficiency = $1-1/r^{(n-1)}$

$r = 8$ Eff = 0.56

- Diesel Cycle
  - Theoretical Efficiency = $1-[1/r^{(n-1)}]*[(r_{co})^n - 1] / [n(r_{co} - 1)]$

$r = 8$ $r_{co} = 2.5$ Eff = 0.46

$r = 16$ $r_{co} = 2.5$ Eff = 0.59

- Dual Cycle
  - Efficiency = $1- [1/r^{(n-1)}]*\{[B(r_{co})^n - 1]+n(r_{co}-1)(1-B)\}/[n(r_{co} - 1)]$
  - Theoretical Efficiency

Lower than Otto Cycle for same compression ratio

Higher than Diesel Cycle for same compression ratio

Engine Cycles

- Otto Cycle
  - Theoretical Efficiency = $1-1/r^{(n-1)}$

$r = 8$ Eff = 0.56

- Diesel Cycle
  - Theoretical Efficiency = $1-[1/r^{(n-1)}]*[(r_{co})^n -1] / [n(r_{co} -1)]$

$r = 8$ $r_{co} = 2.5$ Eff = 0.46

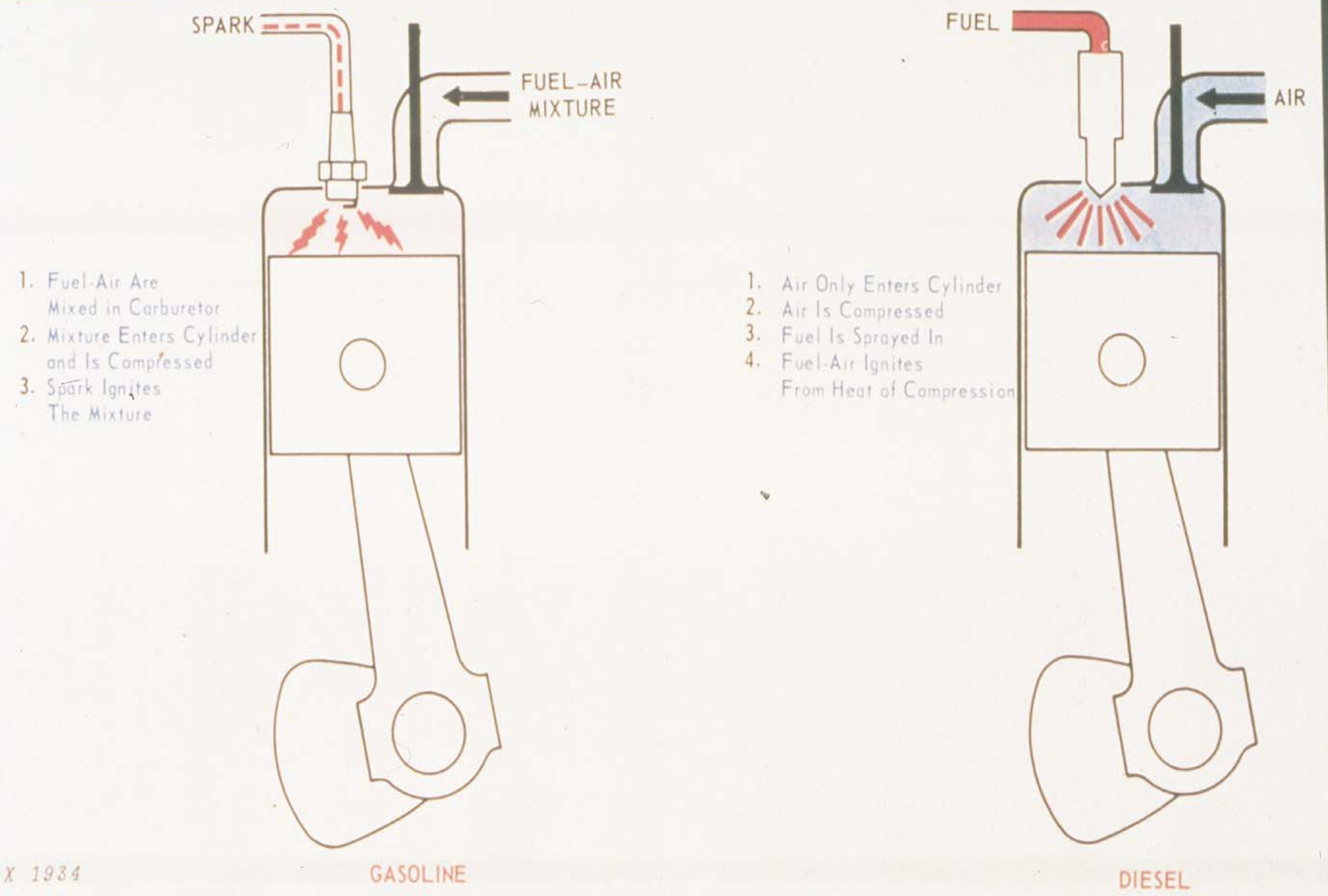
$r = 16$ $r_{co} = 2.5$ Eff = 0.59

- Dual Cycle
  - Efficiency = $1- [1/r^{(n-1)}]*\{[B(r_{co})^n -1]+n(r_{co}-1)(1-B)\}/[n(r_{co} -1)]$
  - Theoretical Efficiency

Lower than Otto Cycle for same compression ratio

Higher than Diesel Cycle for same compression ratio

Differences Between Gasoline And Diesel Engines



1. Fuel-Air Are Mixed in Carburetor
2. Mixture Enters Cylinder and Is Compressed
3. Spark Ignites The Mixture

1. Air Only Enters Cylinder
2. Air Is Compressed
3. Fuel Is Sprayed In
4. Fuel-Air Ignites From Heat of Compression

Fig. 24 — Methods Of Supplying And Igniting Fuel

Characteristics of Four Stroke Compression Ignition & Spark Ignition Engines

Characteristics	Compression-Ignition Engine	Spark- Ignition Engine
Compression Ratio	14-22 : 1	5-8 : 1
Ignition	Compression	Electric Spark
Thermal Efficiency	30-60%	25-30%
Fuel induction	Injector	Carburettor (Fuel Injection)
Fuel System	Fuel Oil / Diesel	Gasoline (LP gas)
Fire Hazard	Less	Greater
Power Variation	Increase in Fuel	Increase in Air/Fuel Mixture
Air Induction	Constant	Variable (Throttle Airflow)
Air-Fuel Ratio	15-100 : 1	10-20 : 1
Relative Fuel Consumption	Lower	Higher
Energy per litre of fuel	Higher	Lower
Manifold Throttle	Absent	Present
Exhaust Gas Temperature	482^o C / 900 F	704^o C / 1300 F
Starting	Harder	Easier
Lubricants	Heavy duty oils	Regular and Premium Oils
Speed Range	Limited (600-3200 rpm)	Wide range (400-6000 rpm)
Engine Mass per Horsepower	8 kg (17.5 lb)	Average 4 kg (9 lb)
Initial Cost	High	Much Lower
Lugging ability (Torque)	Excellent	Less