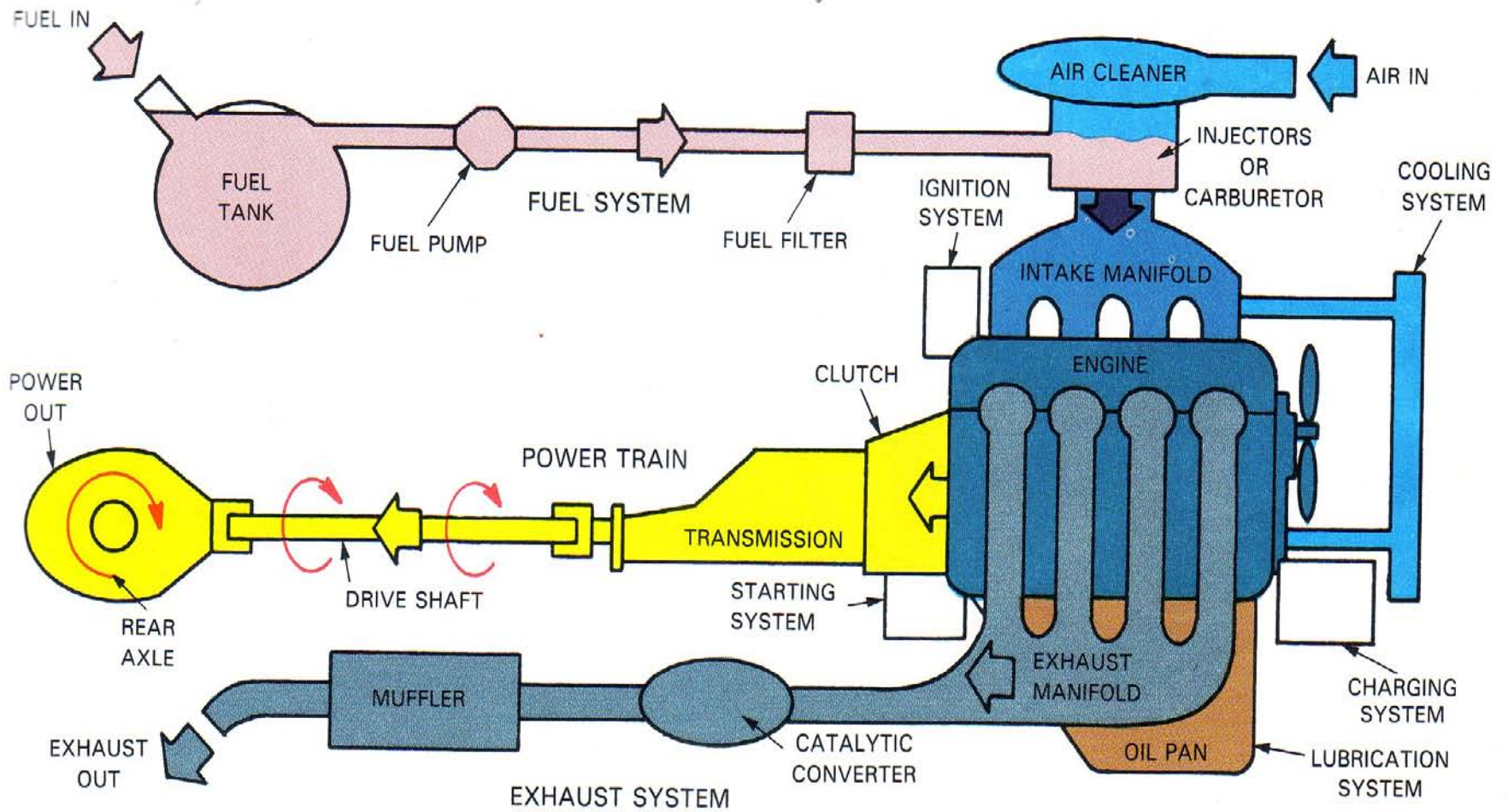# Internal Combustion Engines

University of Al-Basrah
College of Engineering
Mechanical Engineering Department
3rd Stage

II. Engine Power and Performance

FUEL IN

AIR CLEANER — AIR IN

INJECTORS OR CARBURETOR

COOLING SYSTEM

FUEL TANK

FUEL SYSTEM

IGNITION SYSTEM

FUEL PUMP

FUEL FILTER

INTAKE MANIFOLD

POWER OUT

CLUTCH

ENGINE

POWER TRAIN

TRANSMISSION

DRIVE SHAFT

STARTING SYSTEM

REAR AXLE

EXHAUST MANIFOLD

CHARGING SYSTEM

MUFFLER

EXHAUST OUT

CATALYTIC CONVERTER

OIL PAN

LUBRICATION SYSTEM

EXHAUST SYSTEM

✓ *Automotive systems*. Note location of parts. Study flow of fuel, air, exhaust and power.

Preliminary Notes

- Internal combustion engines are so called because the heat required to drive them is released by oxidizing a fuel inside the engine itself.

- This approach has advantages and disadvantages, but is still the most popular for transport and small power generation plant.

- We will be looking at some common types of engine, examining ways of analyzing their performance parameters, and some of the problems encountered in improving efficiency and output .

Preliminary Notes

- Internal combustion engines include systems which function like "closed" systems (e.g. petrol engines) or as "open" (e.g. gas turbines) . systems

All the engines we will examine contain the same basic activities:

- do some work to compress a working fluid,

- release heat into the fluid,

- recover a greater amount of work,

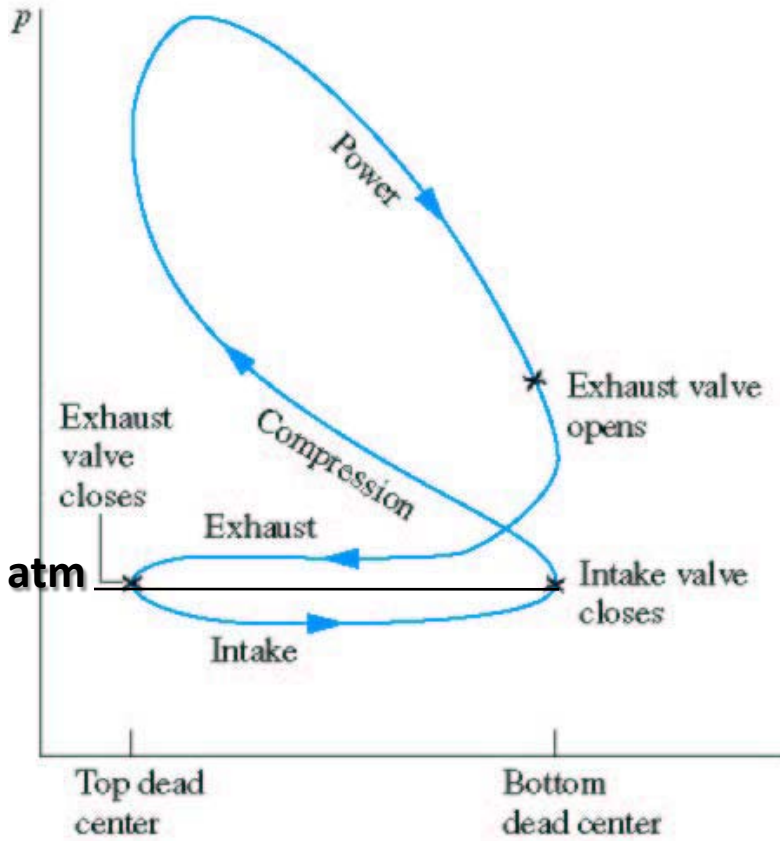- return to initial conditions by removal of some heat.

Review of Otto Cycle

- The Otto Cycle has four basic steps or strokes:

❑ F-A : An intake stroke that draws a combustible mixture of fuel and air into the cylinder

❑ A-B : A compression stroke with the valves closed which raises the temperature of the mixture. A spark ignites the mixture towards the end of this stroke.

❑ C-D : An expansion or power stroke. Resulting from combustion.

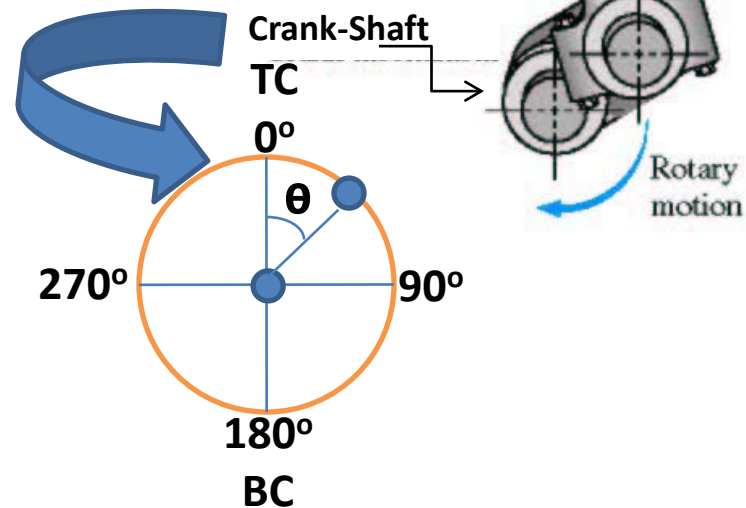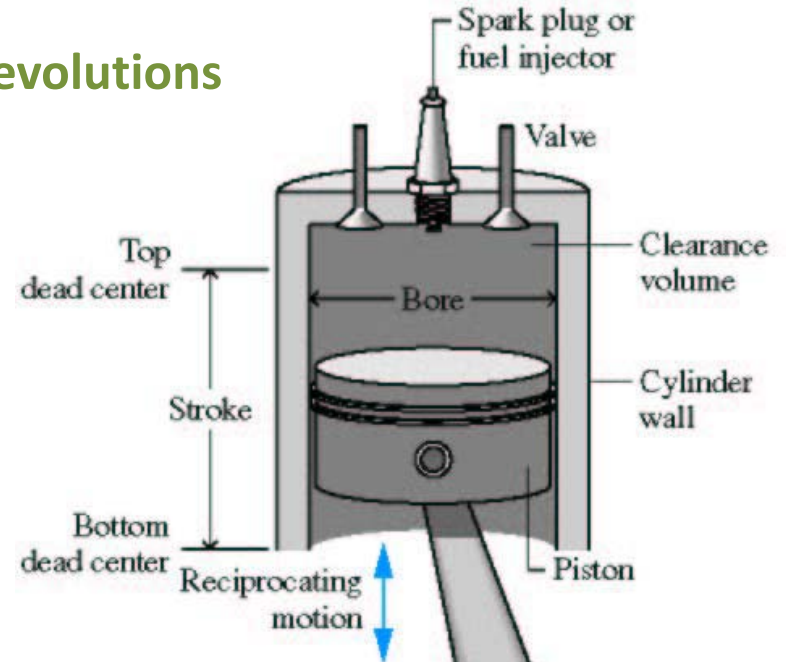❑ E-F : An Exhaust stroke that pushes the burned contents out of the cylinder
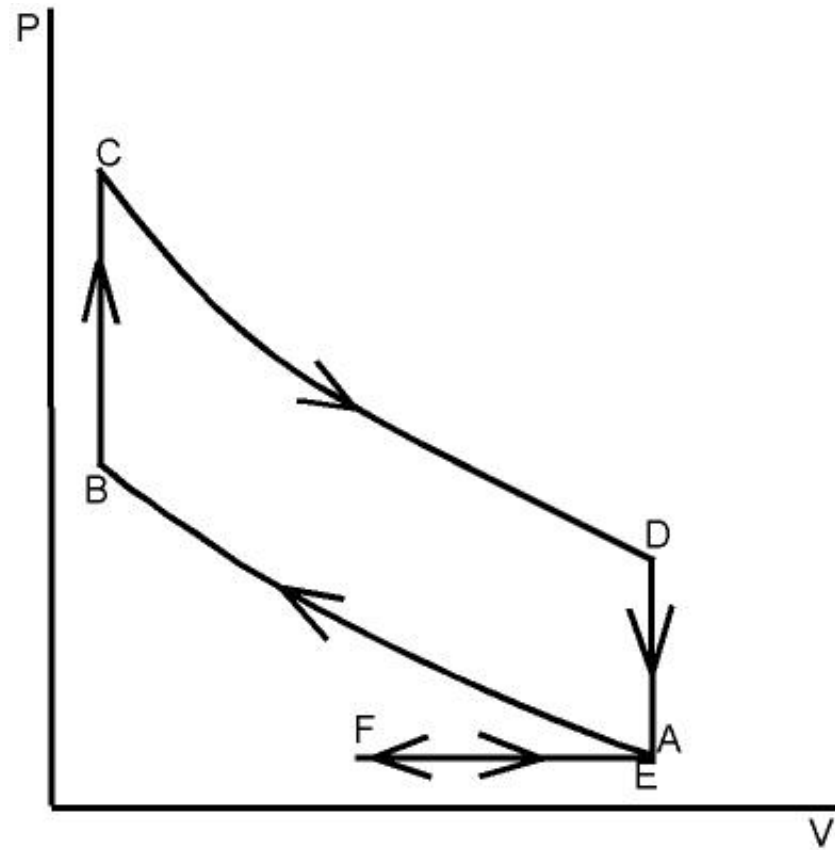
idealized representation of the Otto cycle on a PV diagram.

Otto (SI Engine) Operating Cycle

1 power stroke for every 2 crank shaft revolutions

p

Power

Compression

Exhaust valve opens

Exhaust valve closes

Exhaust

1 atm

Intake valve closes

Intake

Top dead center

Bottom dead center

Cylinder Volume (displacement)

Spark plug or fuel injector

Valve

Top dead center

Bore

Clearance volume

Stroke

Cylinder wall

Bottom dead center

Reciprocating motion

Piston

Crank-Shaft

TC

0º

θ

270º

90º

180º

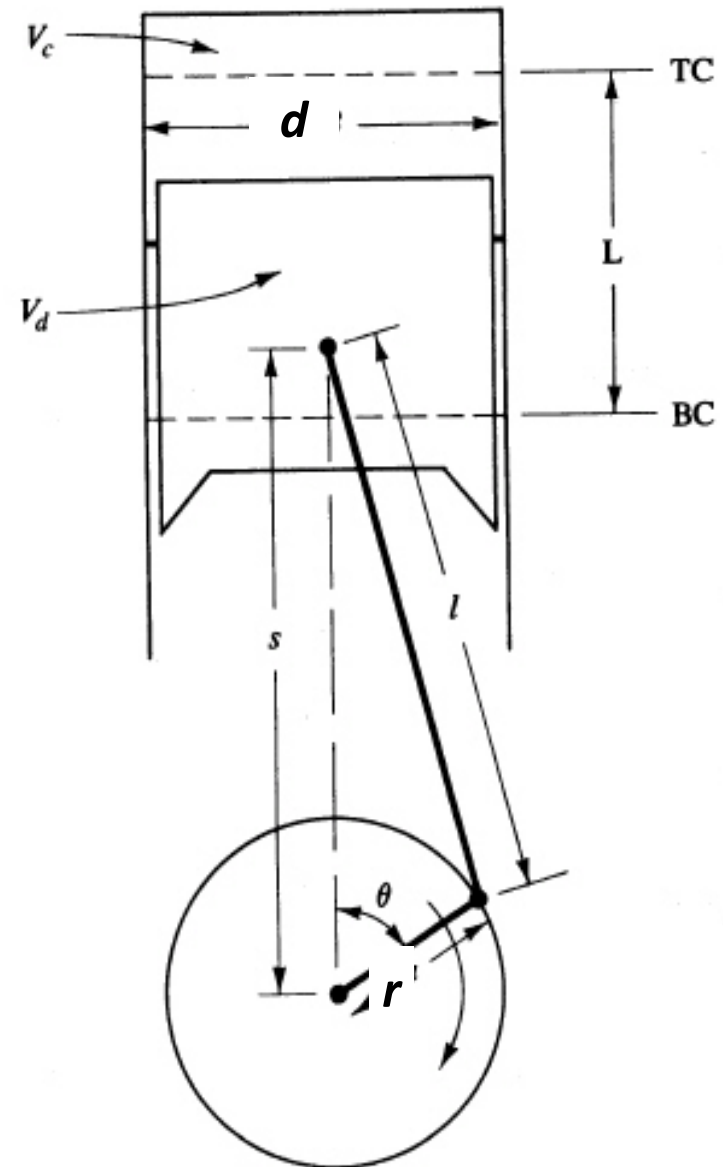**BC**

Rotary motion

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Engine Geometric Parameters

- For an engine with bore (d); crank offset (r), *stroke length L, turning at an engine speed of N:*
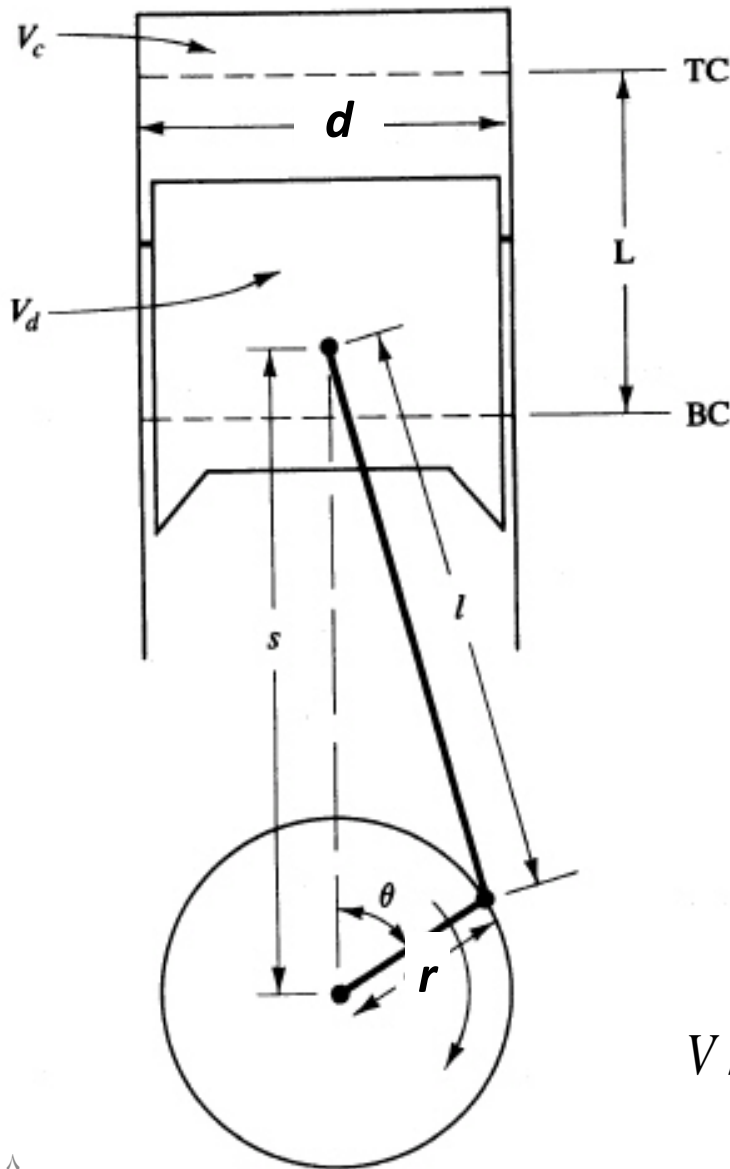
$$L = 2\,r$$

- *An average piston speed is*

$$\overline{U}_p = 2LN$$

- Average piston speed for all engines will normally be in the range of 5 to 15 m/sec with large diesel engines on the low end and high-performance automobile engines on the high end. .....Why?

Engine Geometry Parameters

- The distance (s) between crank axis and gudgeon pin axis is given by

$$s = r.\cos\theta + \sqrt{l^2 - r^2\sin^2\theta}$$

- The cylinder volume (V) at any crank angle is

$$V = V_c + \frac{\pi d^2}{4}(l + r - s)$$

- maximum displacement or swept volume of one cylinder is

$$V_d = \frac{\pi d^2}{4}L = V_{BDC} - V_{TDC}$$

- Cylinder volume (V) at any crank angle can also written in dimensionless form as

$$V/V_c = 1 + \frac{1}{2}(CR-1)\left[\frac{l}{r} + 1 - \cos\theta - \sqrt{\left(\frac{l}{r}\right)^2 - \sin^2\theta}\right]$$

Engine Geometry Parameters

- The combustion chamber surface area is

$$A_s = A_{ch} + A_p + \pi d(l + r - s)$$

$$A_s = A_{ch} + A_p + \left(\frac{\pi d L}{2}\right)\left[\frac{l}{r} + 1 - \cos\theta - \sqrt{\left(\frac{l}{r}\right)^2 - \sin^2\theta}\right]$$

- Where A_{ch} is the cylinder head surface area, A_p is the piston-face area. A_{ch} will be somewhat larger than A_p
- The instantaneous piston speed, U_p = ds/dt

$$U_p / \overline{U}_P = \frac{\pi}{2}\sin\theta\left[1 + \left(\frac{\cos\theta}{\sqrt{(l/r)^2 - \sin^2\theta}}\right)\right]$$

- Average piston speed for standard high performance auto engine is about (2L N = 15 m/s). Therefore engines with large strokes run at lower speeds those with small strokes run at higher speeds.
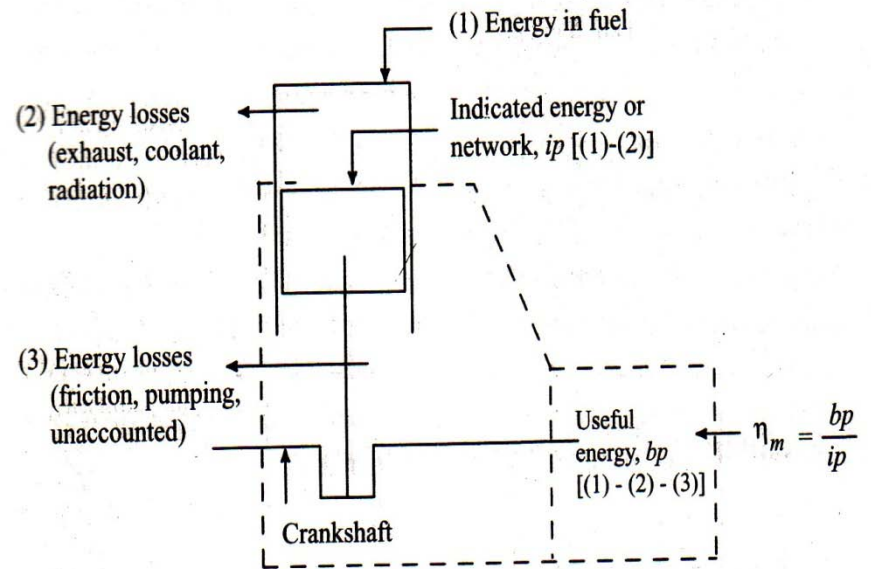
Piston Velocity vs. Crank Angle

- **R is the ratio of connecting rod length to crank offset and usually has values of 3 to 4 for small engines, increasing to 5 to 10 for the largest engine. The effect of R on piston speed is shown in the figure.**

$R = l/r$
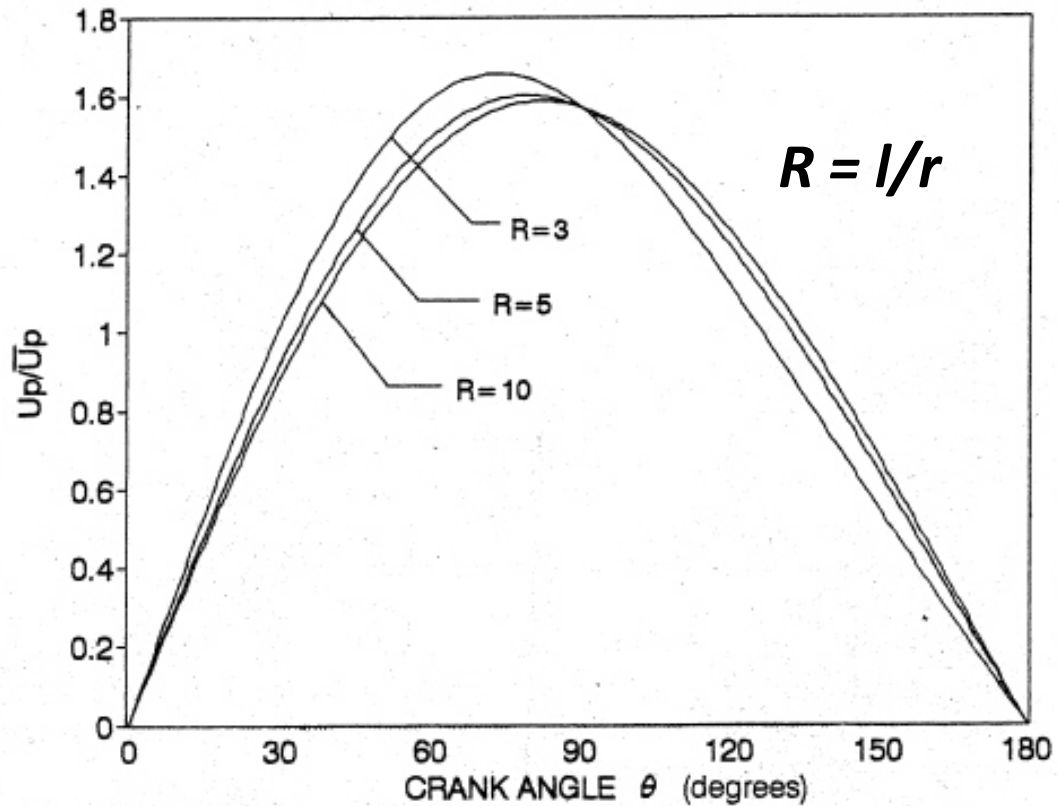
The 1ˢᵗ Law Analysis of Engine Cycle
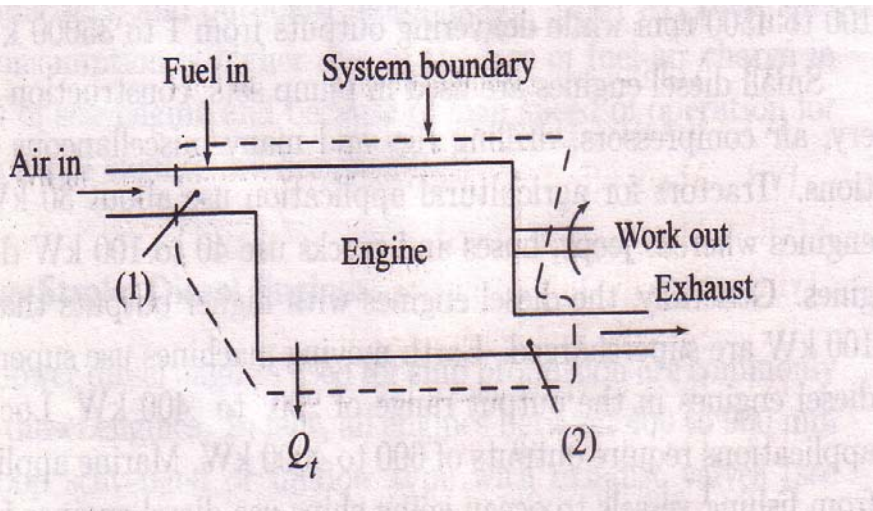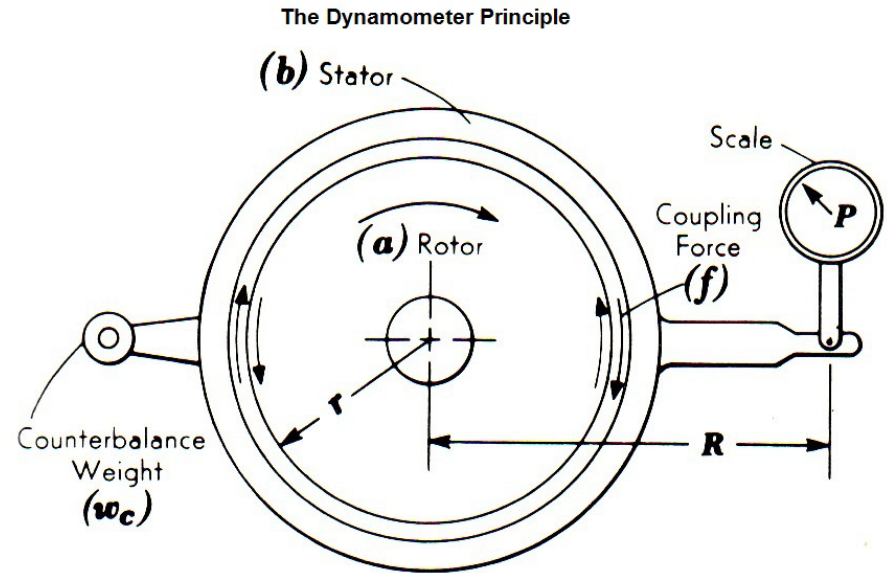

Reciprocating Engine as an Open System

Energy Flow through the Reciprocating Engine

Measurement of Engine Torque and Power

- **Torque** requires the measurement of a force acting through a distance. Any apparatus that permits such a measurement is called a **dynamometer**.

- All dynamometers operate on the principle illustrated in the figure shown .➡

- The rotor (a), driven by the engine to be tested, is coupled (electrically, magnetically, hydraulically or by dry friction) to the stator (b) .

The Dynamometer Principle

(b) Stator

(a) Rotor

Counterbalance Weight **(w_c)**

Scale

Coupling Force **(f)**

r

R

P

- The "scale" shown can be a beam balance or a load cell which has an output either hydraulic pressure or an electrical voltage.
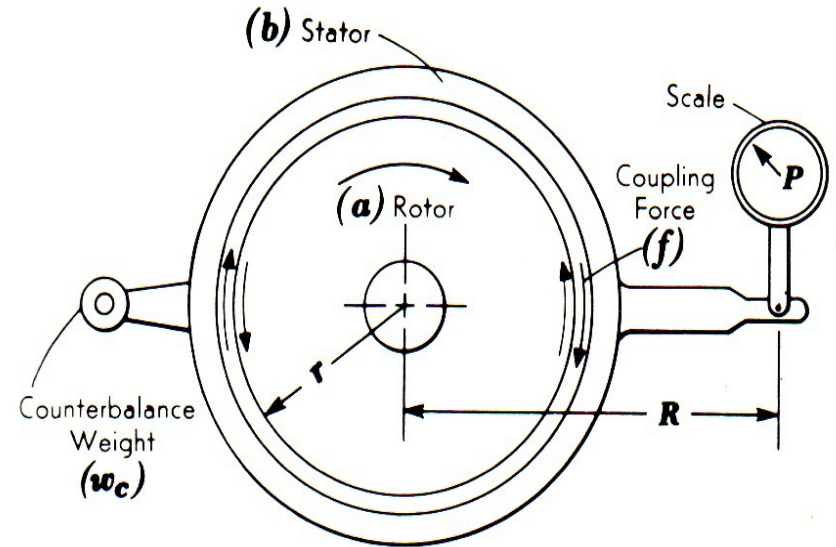
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Measurement of Engine Torque and Power

- In one revolution of the shaft, the periphery of rotor moves a distance (**2πr**) against the coupling force (f) (a drag force).
- The work per revolution is:

$$Work = 2\pi rf$$

- The external moment must just balance the turning moment :

$$rf = PR$$

- **P :** *the scale reading,*
- **R** *: the arm*
- Thus

$$Work = 2\pi RP$$

- For engine speed (N) rpm,

$$Work\ per\ minute = 2\pi RPN$$

- *Power is the time rate of doing work and thus* **(2πRPN)** *is the power.*

Torque and Power

- The magnitude (PR) is called **torque.**
- **Torque** is the twisting or turning moment, visualized as the power per unit rotation (radians).
- **Torque** is the ability of an engine to do work, while power is the **rate** at which the work is done.
- Imagine, the torque determines whether an engine can drive a vehicle through sand or other obstacles,
- **Torque unit is (N-m)**
- **1 ft-lb$_f$ = 1.355 N-m**

- Whereas the power determines how quickly the car progresses over the obstacles.
- Power unit is **(W).**
- Horsepower **(hp)** is:

hp = 0.7457 **kW**

     = 2545 **BTU/hr**

     = 550 **ft-lb$_f$/s**

- 1 kW = 1.341 **hp**

Mean Effective Pressure

Pressure, P

Wide Open
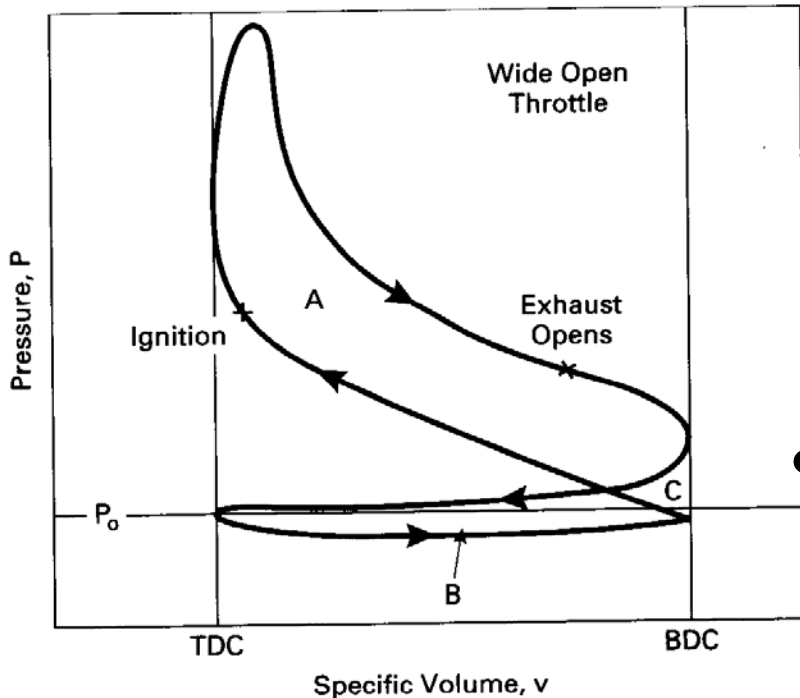Throttle

Ignition

A

Exhaust
Opens

P_o

B

C

TDC

BDC

Specific Volume, v

- The figure shows that pr. in the cylinder is continuously changing during the cycle. A mean effective pr. (mep or P) is defined by:

mep = (work/cycle)/ swept volume

$$W/cycle = P \times V_s$$

- mep is a good parameter to compare engines for design or output because it is independent of engine size.
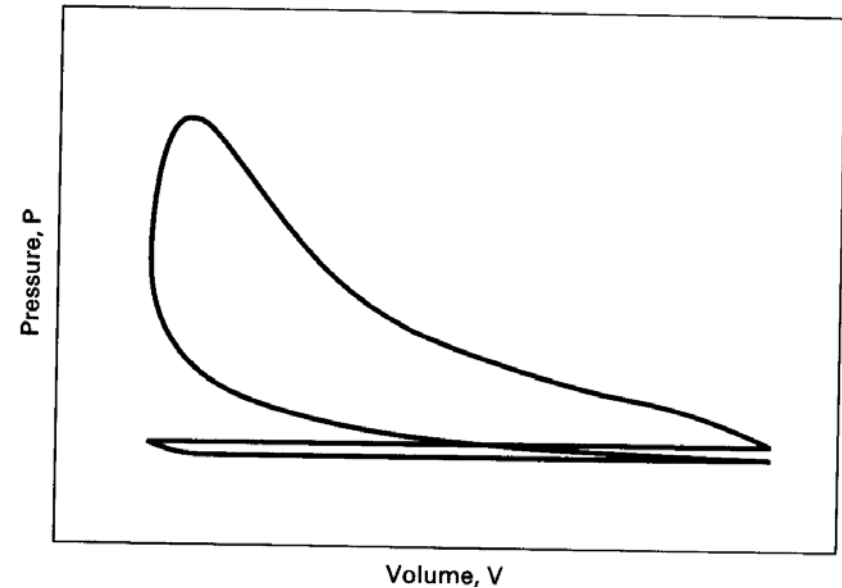
Indicated Mean Effective Pressure (Pi)

Pi = $(a\,/l) \times k$　　　(bar)

a = area of diagram (mm)

l = length of diagram (mm)

k = spring constant (bar/mm)

- see problems 6 &7 P164 in Obert's book.

Indicator diagram for a typical 4-stroke cycle SI engine. An indicator diagram plots cylinder pressure as a function of combustion chamber volume over a 720° cycle.

Indicated Power (IP)

- Is the rate of work done by the gas on the piston.
- Gas force on the piston:

$F = Pi \times A_p$ (N)

- Work per cycle done by the gas on the piston:

$W = F \times L$ (N.m = J)

$W = Pi \times Ap \times L$ (J)

- Power developed per cycle:

$IP = (W/cycle) \times (No.\ of\ cycles\ /\ sec\ )$

- For an engine of (n) cylinders and of speed , N (rev/sec)

$IP = n \times Pi \times A \times L \times (N\ /\ X)$

X = Number of revolutions to complete one cycle

X = 1 .... 2-stroke cycle

X = 2 ....4-stroke cycle

- Note : 1 kW = 1.341 hp

Brake Power (BP) and Friction Power (FP)

- Brake power is the available power of the engine.
- $BP = T \times \omega = 2\pi\,N\,T$ (W)
- Home work : write a brief definition for each of the following types of dynamometers and mention the best type:
- Friction type
- Hydraulic type
- Eddy current type
- Electric type.

- Brake work (delivered by the crank shaft) is less than indicated work due to mechanical friction and parasitic loads of the engine. Parasitic loads include the oil pump, super-charger, air- conditioner compressor, alternator, etc.
- $FP = IP - BP$ (W)

Air-Fuel Ratio (A/F) and Fuel-Air Ratio (F/A)

$$\frac{A}{F} = \frac{m_a}{m_f} = \frac{\dot{m}_a}{\dot{m}_f}$$

$$\frac{F}{A} = \frac{m_f}{m_a} = \frac{\dot{m}_f}{\dot{m}_a} = 1/(A/F)$$

- In the SI engine the A/F ratio is practically remains constant over a wide range of operation. In CI engines at a given speed the air flow does not vary with load. Therefore, the term (F/A) is generally used instead of (A/F).

Brake Mean Effective Pressure (P$_b$) and Specific Fuel Consumption (sfc)

- Brake mean effective pressure is that mean effective pressure acting on the piston which would give the measured brake power if the engine is frictionless:

- IP = n Pi A L N / X ➡ BP

- P$_b$ = BP X / (n A L N)

- Specific fuel consumption is the mass of fuel consumed per (kW) developed per hour, and it is a criterion of economic power production.

$$sfc = \dot{m}_f / Power$$

- Where $\dot{m}_f$ in (kg/hr) and Power in (kW)

Engine Mechanical Efficiency

- Mechanical efficiency of engine is

$$\eta_m = BP/IP = isfc/bsfc = \eta_{tb}/\eta_{ti}$$

- Where

- isfc : indicated specific fuel consumption

$$isfc = \overset{\bullet}{m}_f/IP$$

- bsfc: brake specific fuel consumption

$$bsfc = \overset{\bullet}{m}_f/BP$$

- Also

$$\eta_m = BP/IP = BP/(BP+FP)$$

- Where
- FP : friction power (W)
  FP = IP - BP

Engine Efficiencies

•The time available for the combustion process of an engine cycle is very brief, and not all fuel molecules may find an oxygen molecule with which to combine. A **combustion efficiency (η_c) is defined** to account for the fraction of fuel which burns. For one engine cycle in one cylinder, the rate heat added is:

$$\dot{Q}_{in} = \dot{m}_f\, Q_{HV}\eta_c$$

Thermal efficiency is defined as

$$\eta_t = OutputPower\,/\,\dot{Q}_{in}$$

• Brake thermal efficiency is

$$\eta_{tb} = BP\,/\,\dot{Q}_{in} = BP\,/(\dot{m}_f\, Q_{HV}\eta_c)$$

•Indicated thermal efficiency:

$$\eta_{ti} = IP\,/\,\dot{Q}_{in} = IP\,/(\dot{m}_f\, Q_{HV}\eta_c)$$

• Where

- $\dot{m}_f$ is fuel mass flow rate (kg/s)

-Q_{HV} is heating value of fuel (J/kg)

- η_c is the combustion efficiency

• Fuel conversion efficiency is

$$\eta_f = Power\,/(\dot{m}_f\, Q_{HV}) = 1/(sfc.Q_{HV})$$

Volumetric Efficiency

- Volumetric efficiency is the ratio of the actual mass of air sucked by the engine on the intake stroke to the theoretical mass of air that should have been inducted by filling the piston displacement volume with air at atmospheric temp. and pr. .

$$\eta_v = \dot{m}_{a,act} / \dot{m}_{a,theo}$$

$$\eta_v = \dot{m}_{a,act} / (\rho_a . V_s N / X)$$

- if ρ_a **= constant**

$$\eta_v = \dot{V}_{a,act} / \dot{V}_{a,theo}$$

$$\dot{V}_{a,theo} = V_s N / X$$

- it is also defined as

$$\eta_v = m_a / (\rho_a . V_s)$$

- Standard atmospheric conditions:
  - P_a = 101 kPa
  - T_a = 25 °C

Volumetric Efficiency

- Typical values of volumetric efficiency for an engine at wide-open throttle (WOT) are in the range 75% to 90%, going down to much lower values as the throttle is closed. Restricting air flow into an engine (closing the throttle) is the primary means of power control for a spark ignition engine.

- Notes.
1. Supercharging … η_v >= 100%
2. Vol. eff. depends on engine speed (N), compression ratio (CR), valve timing and valve design, cylinder temp. , atmospheric conditions .. etc.