APPLIED THERMODYNAMICS

Internal Combustion Engines (Module III)

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List of Topics

1. Internal Combustion Engine – Components, Nomenclature and Classifications
2. Basic Engine Cycle and Engine Kinematic Analysis ✓
3. Engine Operating Characteristics
4. Thermodynamic Analysis of Air Standard Cycles
5. Valve Timing Diagram and Fuel – Air Cycle
6. Thermochemistry and Fuel Characteristics
7. Combustion Phenomena in Engines
8. Heat Transfer Analysis in Engines
9. Exergy Analysis and Engine Emission/Pollution

Lecture 2

Basic Engine Cycle and Engine Kinematic Analysis

- Four Stroke Spark Ignition Engine Cycle
- Four Stroke Compression Ignition Engine Cycle
- Two Stroke Spark Ignition Engine Cycle
- Two Stroke Compression Ignition Engine Cycle
- Engine Kinematic Analysis

Basic Engine Cycles

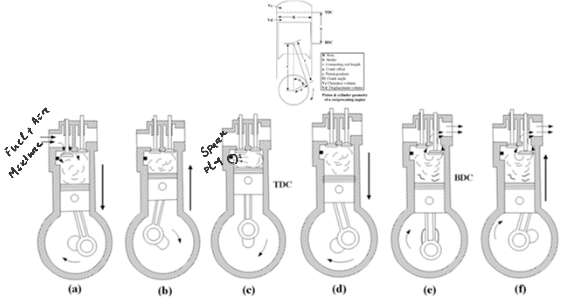
Most internal combustion (IC) engines (both SI & CI) operate on either a four-stroke or two-stroke cycle. These basic cycles are fairly standard for all the engines except slight variation in manufacturing designs.

Nature of Ignition: When the fuel-air combustion process in the engine is initiated with a high voltage discharge by using a "spark plug", then it is called as "spark ignition (SI)" engine. If fuel-air mixture is self-ignited due to high temperature (due to compression) in the combustion chamber, then it is known as "compression ignition (CI)" engine.

Engine Cycle: When there is four piston movements over two engine revolution in each cycle (or one power stroke per two crankshaft revolution), it is called as "four-stroke engine". In the other hand, a "two stroke engine" has two piston movements over one engine revolution in each cycle (or one power stroke per one crankshaft revolution).

Four-Stroke SI Engine Cycle

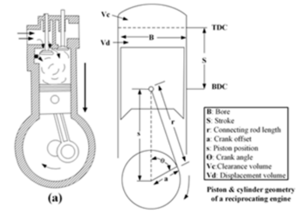
When there is four piston movements over two engine revolution in each cycle (or one power stroke per two crankshaft revolution), it is called as "four-stroke engine".



Four-stroke SI engine operating cycle: (a) Intake stroke – Ingress of air-fuel mixture as piston moves from TDC to BDC; (b) Compression stroke. Piston moves from BDC to TDC. Spark ignition occurs near end of compression stroke; (c) Combustion at almost constant volume near TDC; (d) Power or expansion stroke. High cylinder pressure pushes piston from TDC towards BDC; (e) Exhaust blowdown when exhaust valve opens near end of expansion stroke; (f) Exhaust stroke. Remaining exhaust pushed from cylinder as piston moves from BDC to TDC.

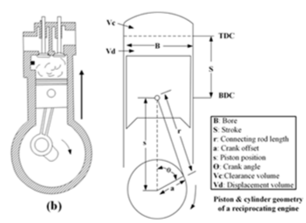
Four-Stroke SI Engine Cycle

- **Intake / Induction (First Stroke)**
  - ➢ **Piston travels from TDC to BDC**
  - ➢ **Intake valve is open and exhaust valve is closed**
  - ➢ **Increase in volume in combustion chamber creates vacuum**
  - ➢ **Pressure differential through intake system and atmosphere (outside) causes air to be inducted into the cylinder**
  - ➢ **Throughout air flow in the intake system, fuel is added simultaneously in desired amount by means of fuel injector or carburetor**



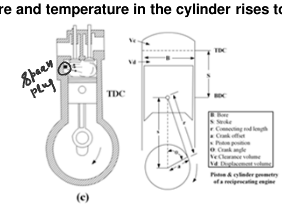
Four-Stroke SI Engine Cycle

- **Compression (Second Stroke)**
  - ➢ **It starts with piston at BDC and both intake & exhaust valve closed**
  - ➢ **Piston travels from BDC to TDC by compressing fuel-air mixture**
  - ➢ **Cylinder pressure and temperature increases due to compression**
  - ➢ **Finite time is required to close the intake valve – thus, actual compression does not start exactly at BDC but after a time lag (aBDC)**
  - ➢ **Near the end of compression stroke, the spark plug is fired to initiate combustion of fuel-air mixture**



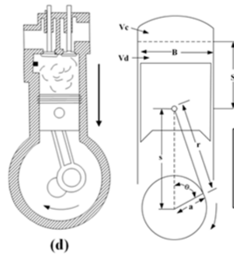
Four-Stroke SI Engine Cycle

- **Combustion**
  - ➢ **Both intake and exhaust valve closed – Thermodynamically, it is viewed as "constant volume combustion"**
  - ➢ **Combustion of air-fuel mixture occurs in a very short duration but finite length of time with piston near TDC**
  - ➢ **Combustion starts at the end of compression stroke (aTDC) and lasts into the power stroke (slightly aTDC)**
  - ➢ **Combustion changes composition of fuel-air mixture to exhaust products and temperature increases to very high peak value**
  - ➢ **Both, pressure and temperature in the cylinder rises to a very high peak value**



Four-Stroke SI Engine Cycle

- **Expansion / Power (Third Stroke)**
  - It starts with piston at TDC and both intake & exhaust valve closed
  - High pressure generated through combustion process pushes piston from TDC to BDC
  - It produces work output of the engine cycle
  - The cylinder volume increases, thereby pressure and temperature drops

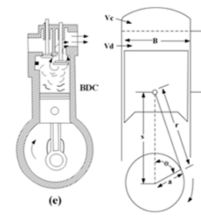


Piston & cylinder geometry of a reciprocating engine

(d)

Four-Stroke SI Engine Cycle

- **Exhaust Blowdown**
  - Towards end of power stroke (near BDC), the exhaust valve opens with inlet valve closed
  - High pressure hot gases comes out the exhaust system due to pressure differential between cylinder and atmosphere
  - Opening of exhaust valve before BDC reduces work output during power stroke but it is required since finite time is needed for blowdown
  - Exhaust gases have high enthalpy and thus lowers cycle efficiency



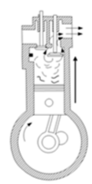
Piston & cylinder geometry of a reciprocating engine

(e)

Four-Stroke SI Engine Cycle

When there is four piston movements over two engine revolution in each cycle (or one power stroke per two crankshaft revolution), it is called as "four-stroke engine".

- **Exhaust (Fourth Stroke)**
  - By the time piston in BDC, the exhaust blowdown is complete
  - Cylinder is full of combustion products almost at atmospheric pressure
  - With inlet valve closed and exhaust valve still remaining open, piston travels from BDC to TDC
  - All remaining gases comes out of the cylinder from the exhaust system except some trapped gases near the clearance volume when the piston is at TDC
  - At the end of exhaust stroke (bTDC), the intake valve starts to open and fully open when the piston reaches at TDC – the engine starts a next cycle i.e. intake stroke
  - Near TDC, the exhaust valve also starts to close and becomes fully closed sometimes after TDC (aTDC). The period for which both valves remain open is known as "valve overlap".



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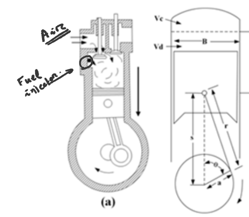
Four-Stroke CI Engine Cycle

- **Intake / Induction (First Stroke)**
  - It starts with piston at TDC and both intake & exhaust valve closed
  - The piston travels from TDC to BDC
  - Intake valve open and exhaust valve closed
  - Increase in volume in combustion chamber creates vacuum
  - Pressure differential through intake system and atmosphere (outside) causes air to be inducted into the cylinder
  - Unlike SI engine cycle, no fuel is added to the incoming air

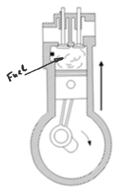


Piston & cylinder geometry of a reciprocating engine

(a)

Four-Stroke CI Engine Cycle

- <u>Compression (Second Stroke)</u>
  - It starts with piston is at BDC and both intake & exhaust valves are closed
  - The piston travels from BDC to TDC by compressing the air
  - The cylinder pressure and temperature increases due to compression
  - Towards end of compression stroke, fuel is injected directly into the combustion chamber where it mixes with hot air
  - Fuel evaporates and self ignites causing combustion to start



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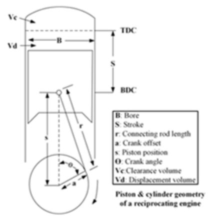
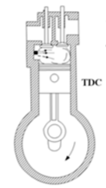


Piston & cylinder geometry of a reciprocating engine

Four-Stroke CI Engine Cycle

- <u>Combustion</u>
  - When piston is at TDC, the combustion process is fully-developed
  - The process continues till the fuel injection is complete
  - Both intake and exhaust valves are closed. Thermodynamically, it is viewed as “constant pressure” combustion
  - Combustion changes composition of fuel-air mixture to exhaust products and temperature increases to very high peak value
  - Both, pressure and temperature in the cylinder rises to a very high peak value
  - Piston prepares to move towards BDC



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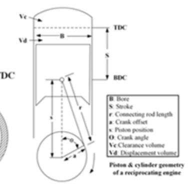
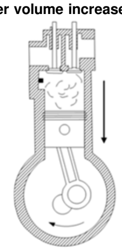


Piston & cylinder geometry of a reciprocating engine

Four-Stroke CI Engine Cycle

- <u>Expansion / Power (Third Stroke)</u>
  - It starts with piston at TDC and both intake & exhaust valve closed
  - The high pressure generated through combustion process pushes piston from TDC to BDC
  - Power stroke continues till the combustion ends
  - It produces work output of the engine cycle
  - The cylinder volume increases, thereby pressure and temperature drops



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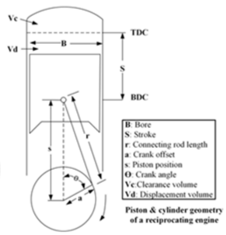

Piston & cylinder geometry of a reciprocating engine

Four-Stroke CI Engine Cycle

- <u>Exhaust Blowdown</u>
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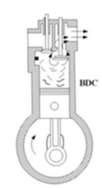
  - Exhaust gases have high enthalpy and thus lowers cycle efficiency



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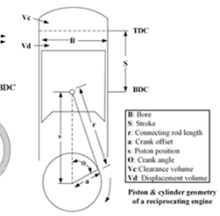

Piston & cylinder geometry of a reciprocating engine

Four-Stroke CI Engine Cycle

When there is four piston movements over two engine revolution in each cycle (or one power stroke per two crankshaft revolution), it is called as "four-stroke engine".

- **Exhaust (Fourth Stroke)**
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  - With inlet valve closed and exhaust valve still remaining open, piston travels from BDC to TDC
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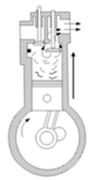
  - At the end of exhaust stroke (bTDC), the intake valve starts to open and fully open when the piston reaches at TDC – the engine starts a next cycle i.e. intake stroke
  - Near TDC, the exhaust valve also starts to close and becomes fully closed sometimes after TDC (aTDC). The period for which both valves remain open is known as "valve overlap".



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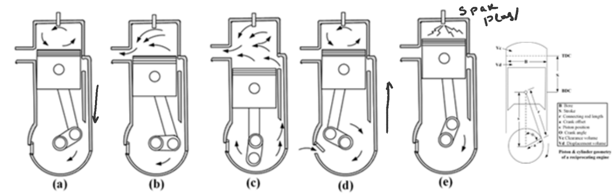
Two-Stroke SI Engine Cycle

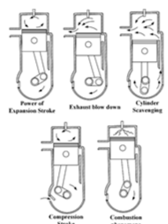
A "two stroke engine" has two piston movements over one engine revolution in each cycle (or one power stroke per one crankshaft revolution).

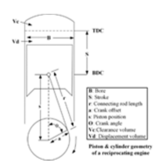


Two-stroke SI engine cycle with crankcase compression: (a) Power/Expansion stroke – High cylinder pressure pushes piston from TDC towards BDC with all ports closed. Air in crankcase compressed by downward motion of the piston; (b) Exhaust blowdown when exhaust port opens near end of power stroke; (c) Cylinder scavenging when intake port opens and air-fuel is forced into the cylinder under pressure. Intake mixture pushed some of the remaining exhaust out of open exhaust port. Scavenging lasts till piston passes BDC and closes intake and exhaust ports. (d) Compression stroke – Piston moves from BDC to TDC with all ports closed. Intake air fills crankcase, Spark ignition occurs near end of stroke; (e) Combustion at almost constant volume near TDC.

Two-Stroke SI Engine Cycle

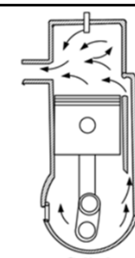
- **Combustion**
  - When piston is at TDC, the combustion process occurs quickly
  - The process continues till the fuel injection is complete
  - Thermodynamically, it is viewed as "constant volume" combustion
- **Expansion / Power (First Stroke)**
  - Very high pressure generated through combustion process pushes piston from TDC to BDC
  - Cylinder volume increases, thereby pressure and temperature drops
  - Produces work output of the engine cycle
- **Exhaust blowdown**
  - Much ahead of BDC (75° bBDC), the exhaust valve opens and blow down occurs
  - After blowdown, the cylinder remains filled with exhaust gases at low pressure



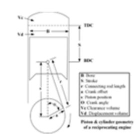


Two-Stroke SI Engine Cycle

- **Intake and Scavenging**
  - On near completion of blowdown (50° bBDC), the intake slot on one side of the cylinder is uncovered so that intake air-fuel mixture enters under pressure. Fuel can be added to air with either a carburetor or fuel injection.
  - This incoming mixture pushes exhaust products out of exhaust valve and fills the cylinder with combustible air-fuel mixture.
  - This mechanism in a two-stroke cycle is called as "scavenging".
  - The piston then passes very quickly BDC and covers intake port and then exhaust valve also closes.
  - The high pressure at which air enters the cylinder is established in two ways: the crankcase in normal engines (in addition to its other function) is designed to serve as compressor and large two-stroke cycles use superchargers.

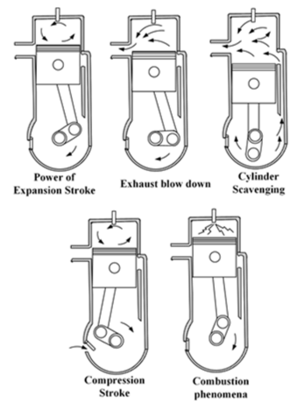


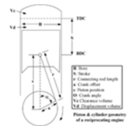
Cylinder Scavenging



Two-Stroke SI Engine Cycle

- Compression (Second Stroke)
  - All valves/ports are closed and piston travels from BDC to TDC
  - Combustible air-fuel mixture is compressed to a high value.
  - This mechanism in a two-stroke cycle is called as "scavenging".
  - Near the end of compression (in the vicinity of piston position at TDC), spark plug is fired.
  - By the time piston gets to TDC, the combustion occurs and next engine cycle begins.



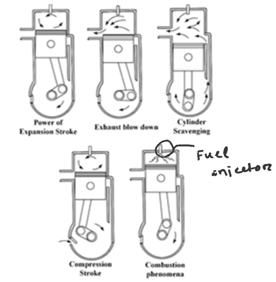


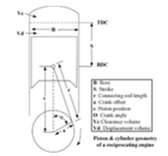
21

Two-Stroke CI Engine Cycle

It is similar to SI engine cycle except two important changes:

- No fuel is added to incoming air so that only air is compressed
- Fuel injector is located in the cylinder instead of spark plug
- Towards end of compression stroke, fuel is injected into hot compresses air
- Combustion is initiated through self-ignition of the fuel
- The biggest draw backs of two-stroke cycle are
  - ✓ Reduced power as compared to four-stroke cycle
  - ✓ Combustion products always dilutes the fresh mixture
  - ✓ Less cycle efficiency than four-stroke cycle

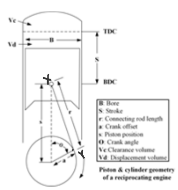




22

Engine Kinematic Analysis

A simplified version of engine nomenclature is shown figure has certain important engine parameters such as piston bore & stroke, connecting rod, crank length. The motion of piston inside the cylinder can be represented through engine kinematic analysis.



Engine RPM, N; Stroke length, $S = 2a$; Crank offset, $a = \frac{S}{2}$; $R = \frac{r}{a}$

x Y = r
Length of connecting rod.

Distance between crank axis and wrist position, $s = a\cos\theta + \sqrt{r^2 - a^2\sin^2\theta}$

Instantaneous piston speed, $U_p = \frac{ds}{dt}$; Average piston speed, $\bar{U}_p = 2SN$

$$\frac{U_p}{\bar{U}_p} = \left(\frac{\pi}{2}\right)\sin\theta\left[1 + \frac{\cos\theta}{\sqrt{R^2 - \sin^2\theta}}\right]$$

Displacement volume/Swept volume, $V_d = V_{BDC} - V_{TDC} = \frac{\pi}{4}B^2S$

An engine with k no. of cylinder, $V_d = k\left(\frac{\pi}{4}B^2S\right)$; Clearance volume, $V_c = V_{TDC}$

Total volume, $V_{BDC} = V_d + V_c$; Compression ratio, $r_c = \frac{V_{BDC}}{V_{TDC}} = \frac{V_d + V_c}{V_c}$

Instantaneous cylinder volume at any crank angle, $V = V_c + \left(\frac{\pi B^2}{4}\right)(r + a - S)$

In non-dimensional form: $\frac{V}{V_c} = 1 + \frac{1}{2}(r_c - 1)\left[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}\right]$

23

Engine Kinematic Analysis

Some of the important inferences with respect to realistic practical parameters are given below:

- Piston speed of an engine determines the instantaneous flow rate of charge (air-fuel mixture) into and out of the cylinder. Large piston speed implies higher amount of charge.
- The range of acceptable piston speed depends on engine speed and size. Based on the safe limit of engine materials use, the maximum average piston speed for various engines are in the range of 5-20 m/s.
- The engine size and its operating speed bear a strong inverse correlation.
  - Large engines (bore size ~ 0.5 m): 200 to 400 rpm
  - Small engine (bore size ~ 10 mm): 12000 rpm
  - Automobile engines: 500 to 5000 rpm (typically 2500 rpm)
  - Racing cars: 10000 rpm

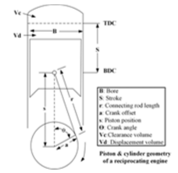
24

Engine Kinematic Analysis

- Stroke to bore ratio allows compromise between thermal efficiency and friction losses. Larger stroke implies higher piston speed but with increase in friction power resulting reduction in net output power.
- Modern automobiles have near-square engine as a design compromise but very large engines have stroke to bore ratio around 4. However, marine applications use larger bore engines.
- The compression ratio for engines can vary between 8-11 (SI engines), 12-24 (CI engines) and 2-3 (engines with turbocharger and/or supercharger)
- Typical values of engine displacement (in terms of cc, 1L = 0.001m^3 = 1000cm^3 = 1000cc) are given below.
  - Modern automobiles: 1500 to 2500cc
  - Large ship engines: 8000cc
  - Small engine: 0.1cc

Numerical Problems

Q1. An automobile engine has 3-litre, 6-cylinder that operates in SI mode on 4-stroke cycle. The CR of the engine is 9.5 an the length of connecting rod of the engine is 170 mm. The engine runs at 3600rpm and the combustion ends at 20°aTDC. Calculate, (i) cylinder bore and stroke; (ii) average piston speed; (iii) clearance volume of each cylinder; (iv) piston speed at the end of the combustion; (v) volume in the combustion chamber at the end of combustion.



Piston & cylinder geometry of a reciprocating engine

Soln (i) Assume $B = S$. $\frac{\pi}{4} B^3 = V_d$. $V_d = \frac{3L}{6} = 0.5L = 0.0005\ m^3$

$B = 0.088\ m = 8.8\ cm$.

$S = 8.8\ cm$.

(ii) $\bar{U}_p = 2SN$ $N = 3600\ rpm$ $\bar{U}_p = 10.6\ m/s$.

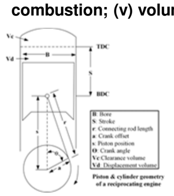
(iii) $CR = r_c = \frac{V_d + V_c}{V_c} = 9.5$

$\Rightarrow \frac{0.0005 + V_c}{V_c} = 9.5$

$\Rightarrow V_c = 0.00006\ m^3 = 60\ cm^3$

Numerical Problems

Q1. An automobile engine has 3-litre, 6-cylinder that operates in SI mode on 4-stroke cycle. The CR of the engine is 9.5 an the length of connecting rod of the engine is 170 mm. The engine runs at 3600rpm and the combustion ends at 20°aTDC. Calculate, (i) cylinder bore and stroke; (ii) average piston speed; (iii) clearance volume of each cylinder; (iv) piston speed at the end of the combustion; (v) volume in the combustion chamber at the end of combustion.



Piston & cylinder geometry of a reciprocating engine

(iv) $\frac{U_p}{\bar{U}_p} = \frac{\pi}{2} \sin\theta \left[1 + \frac{\cos\theta}{\sqrt{R^2 - \sin^2\theta)}}\right]$ $R = \frac{r}{a}$, $a = S/2$

$S = 88\ mm$.

$r = 170\ mm$.

$\frac{U_p}{\bar{U}_p} = 0.668$. $\bar{U}_p = 10.6\ m/s$

$U_p = 7.08\ m/s$.

(v) $\frac{V}{V_c} = 1 + \frac{1}{2}(r_c - 1)\left[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta)}\right]$

$\theta = 20^0$ $r_c = 9.5$ $\frac{V}{V_c} = 1.34$

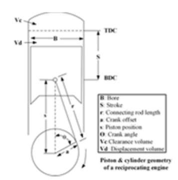
$V_c = 60\ cm^3$ $V = 80.5\ cm^3$

Numerical Problems

Q2. Consider a four-stroke engine running at 500, 1500, 3000, 5000, 12000rpm. How long each revolution lasts for above speeds?

RPM	RPS	Time
500	$\frac{500}{60} = 8.33$	$\frac{1}{8.33} = 0.12\ s$.
1500	25	0.04 s
3000	50	0.02 s
5000	83.3	0.012 s
12000	200	0.005 s

drops



Piston & cylinder geometry of a reciprocating engine

THANK YOU