

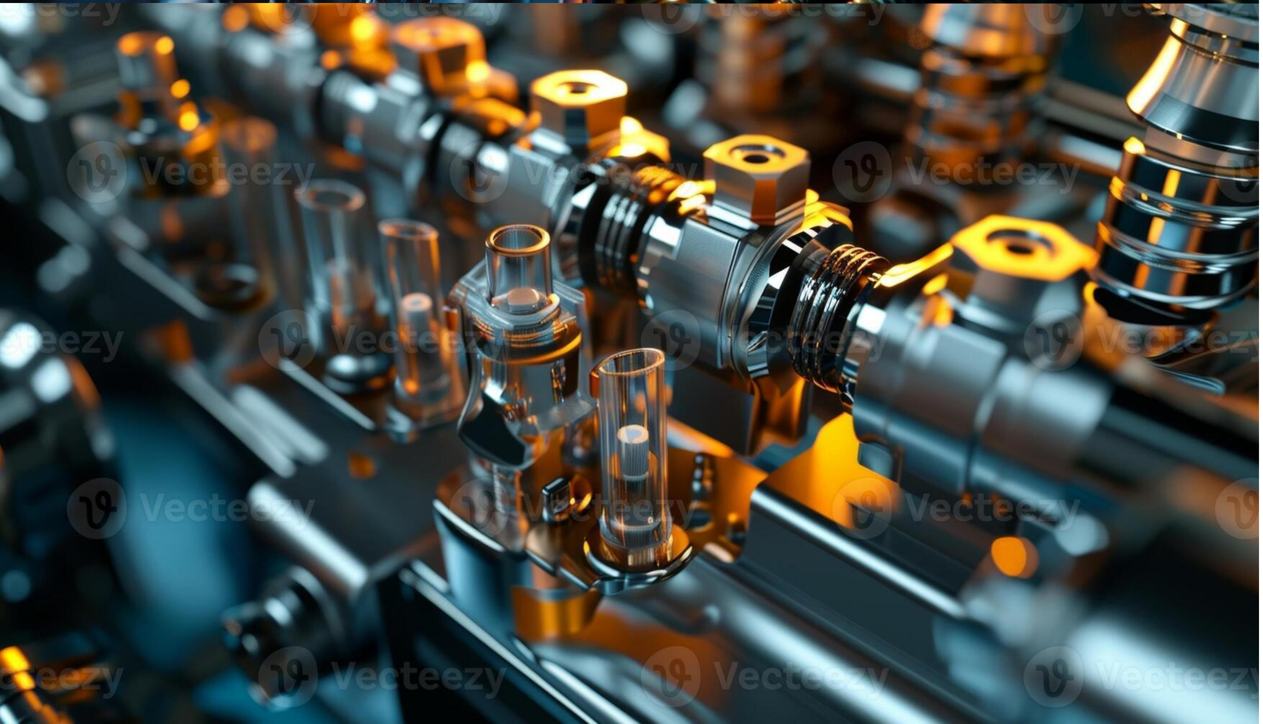

U G V
UNIVERSITY OF GLOBAL VILLAGE

Internal Combustion Engine

Prepared by
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Department of Mechanical Engineering
University of Global Village

Basic Course Information

Course Title	Internal Combustion Engine
Course Code	ME-417
Credits	03
CIE Marks	90
SEE Marks	60
Exam Hours	2hours (Mid Exam) 3hours (Semester Final Exam)
Level	7th Semester
Academic Session	Winter 2025

ASSESSMENT PATTERN

CIE- Continuous Internal Evaluation (90 Marks)

Bloom's CategoryMarks (out of 90)	Tests (45)	Assignments (10)	Class Test (20)	Quiz (5)	External Participation in Curricular/Co-Curricular Activities (10)
Remember	5		10	05	
Understand	5	05	10		
Apply	10				10
Analyze	15				
Evaluate	10				
Create		05			

SEE- Semester End Examination (60 Marks)

Bloom's Category	Test
Remember	10
Understand	10
Apply	10
Analyze	10
Evaluate	10
Create	10

Course Learning Outcomes

- **CLO 1:** Demonstrate an understanding of the fundamental principles of internal combustion engine operation, including thermodynamic cycles, combustion processes, and engine components.
- **CLO 2:** Analyze and diagnose common engine performance issues, such as fuel consumption, emissions, and power output.
- **CLO 3:** Select and apply appropriate maintenance and repair procedures for various types of internal combustion engines.
- **CLO 4:** Evaluate and compare the performance and environmental impact of different internal combustion engine technologies, such as gasoline, diesel, and alternative fuel engines.

Course Objectives

The objectives of an Internal Combustion Engine course are to:

- ❖ To convert the chemical energy stored in fuel into mechanical work with maximum efficiency.
- ❖ To provide consistent and dependable power output over a long service life.
- ❖ To produce significant power output relative to its size and weight, making it suitable for mobile applications.
- ❖ To maximize the amount of work produced per unit of fuel consumed, minimizing operating costs.
- ❖ To reduce harmful emissions such as carbon monoxide, nitrogen oxides, and particulate matter, minimizing environmental impact.
- ❖ To minimize vibrations and noise levels, enhancing user comfort and experience.

Course Summary

Serial No	Course Content	Hours
01.	Basic components and terminology of IC engines, classification of IC engines and their application; working principles of four stroke and two stroke engines - petrol/diesel engine	5
02.	Engine kinematics and performance parameters; autoignition and abnormal combustion, fundamentals of knocking/detonation in SI engines and CI engines.	5
03.	factors influencing knock/detonation, control of knock/detonation; basics of homogeneous charge compression ignition (HCCI) engines, direct injection spark ignition (DISI) engines	15
04.	Complete and incomplete combustion; combustion stoichiometry: mass basis and volume basis; equivalence ratio and mixture strength	15

Course Summary

Serial No	Course Content	Hours
05.	lean and rich combustion; thermochemical calculations: enthalpy of formation, adiabatic flame temperature;	5
06.	types of flame: laminar and turbulent flame, premixed and diffusion flame, factors influencing flame velocity; combustion processes: surface or flameless combustion.	5

Course Plan Mapped with CLO

Week No.	Topics	Teaching Learning Strategy	Assessment strategy	Alignment To CLO
1.	Basic components and terminology of IC engines, classification of IC engines and their application	Lecture, Multimedia	Feedback, Q&A	CLO 1
2.	working principles of four stroke and two stroke engines - petrol/diesel engine.	Lecture, Discussion Multimedia	Feedback, Q&A	CLO 1
3.	Engine kinematics and performance parameters; autoignition and abnormal combustion.	Lecture, Multimedia	Feedback, Q&A	CLO 2
4.	fundamentals of knocking/detonation in SI engines and CI engines.	Lecture, Multimedia	Feedback, Q&A	CLO 2

Course Plan Mapped with CLO

Week No.	Topics	Teaching Learning Strategy	Assessment strategy	Alignment To CLO
5.	influencing knock/detonation, control of knock/detonation	Lecture, Multimedia	Feedback, Q&A	CLO 2
6.	basics of homogeneous charge compression ignition (HCCI) engines, direct injection spark ignition (DISI) engines	Lecture, Discussion Multimedia	Feedback, Q&A	CLO 2
7.	Complete and incomplete combustion	Lecture, Multimedia	Feedback, Q&A	CLO 3
8.	combustion stoichiometry: mass basis and volume basis; equivalence ratio and mixture strength,	Lecture, Multimedia	Feedback, Q&A	CLO 3

Course Plan Mapped with CLO

Week No.	Topics	Teaching Learning Strategy	Assessment strategy	Alignment To CLO
9.	lean and rich combustion;	Lecture, Multimedia	Feedback, Q&A	CLO 3
10.	Thermochemical calculations	Lecture, Discussion Multimedia	Feedback, Q&A	CLO 3
11.	enthalpy of formation, adiabatic flame temperature	Lecture, Multimedia	Feedback, Q&A	CLO 4
12.	types of flame: laminar and turbulent flame, premixed and diffusion flame	Lecture, Multimedia	Feedback, Q&A	CLO 4

Course Plan Mapped with CLO

Week No.	Topics	Teaching Learning Strategy	Assessment strategy	Alignment To CLO
13.	factors influencing flame velocity	Lecture, Multimedia	Feedback, Q&A	CLO 4
14.	combustion processes	Lecture, Discussion Multimedia	Feedback, Q&A	CLO 4
15.	surface or flameless combustion	Lecture, Multimedia	Feedback, Q&A	CLO 4
16.	emissions measurement and control	Lecture, Multimedia	Feedback, Q&A	CLO 4

❖ Week 01

❑ Textbooks

- ✓ **Internal Combustion Engine Fundamentals** by John B. Heywood
- ✓ **Engineering Fundamentals of the Internal Combustion Engine** by Willard W. Pulkrabek
- ✓ **An Introduction to Combustion Concepts and Applications** by Stephen R. Turns

❑ Reference books

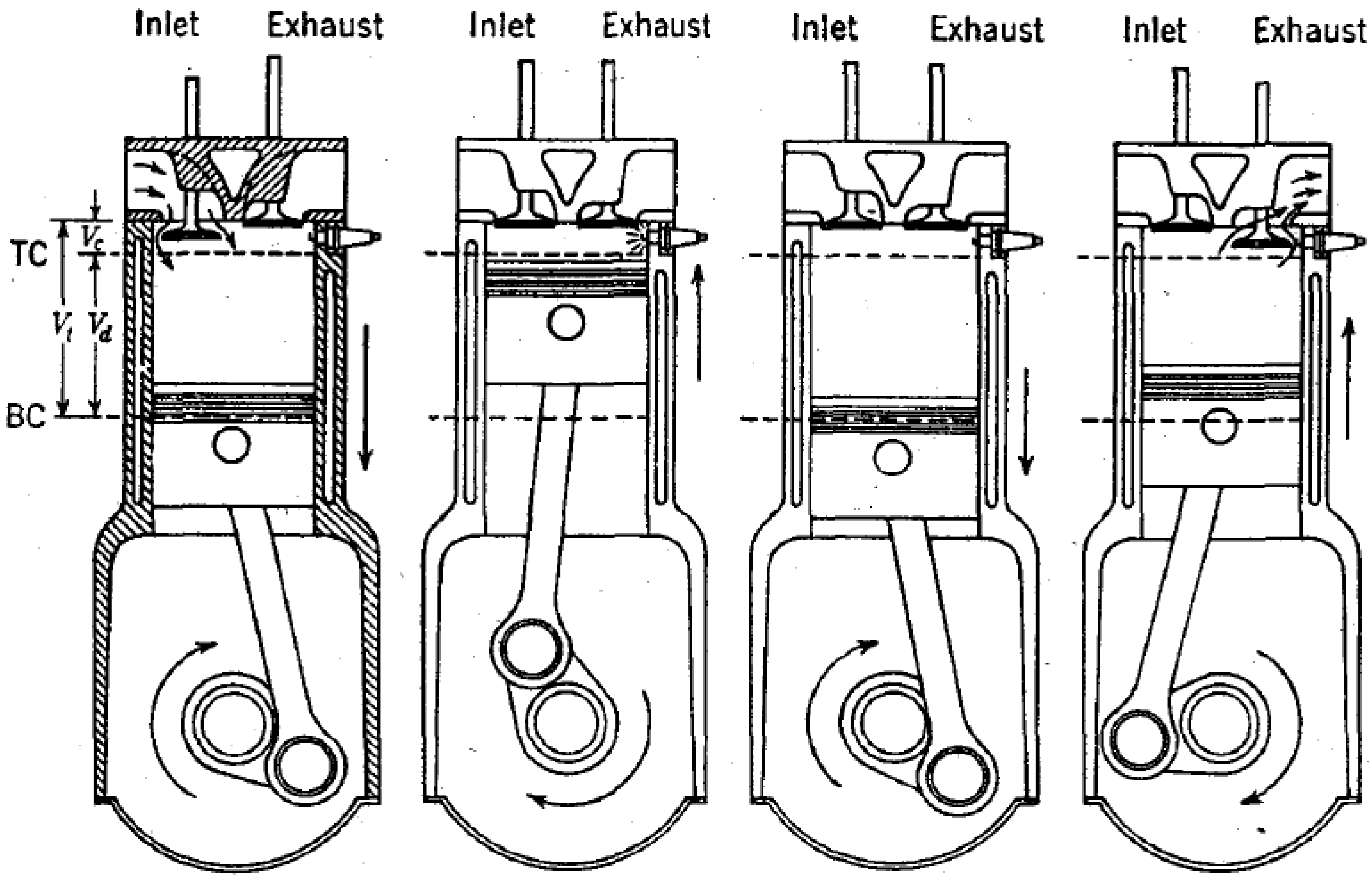
- ✓ **Internal Combustion Engines-Applied Thermosciences,** by Colin R. Ferguson and Allan T. Kirkpatrick
- ✓ **Internal Combustion Engine** by ML Mathur and RP Sharma
- ✓ **Internal Combustion Engines and Air Pollution** by EF Obert

❑ IC Engine

Chemical energy —Combustion→ Thermal energy —Expansion→ Mechanical Energy/ Work

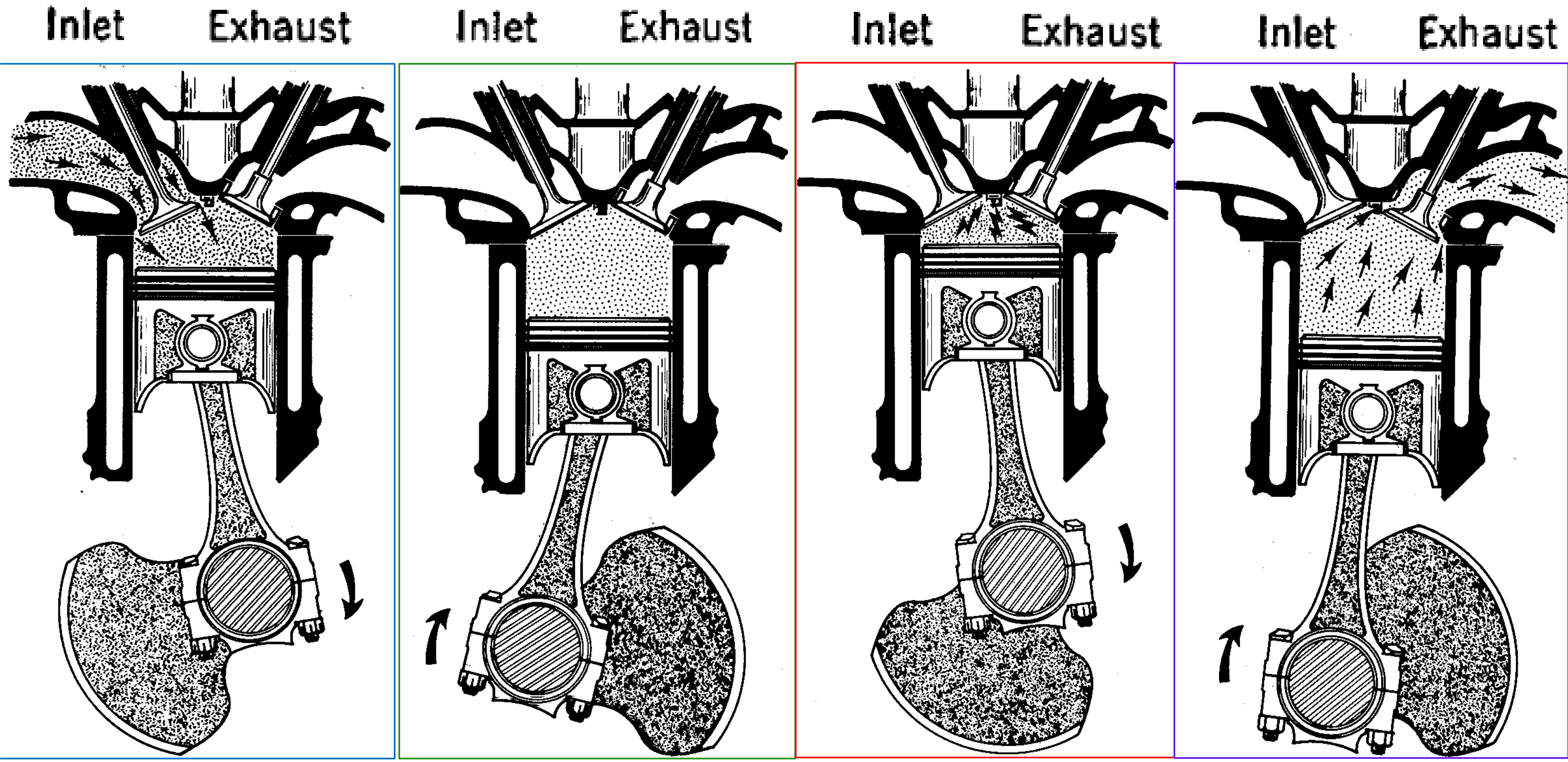
- Converts **chemical energy**, contained in the **fuel** into useful **work** (mechanical energy)

Sequence of Operations of IC Engine



(*a*) Intake (*b*) Compression (*c*) Expansion (*d*) Exhaust

Sequence of Operations of IC Engine



(*a*) Intake (*b*) Compression (*c*) Expansion (*d*) Exhaust

❑ Internal Combustion Engine

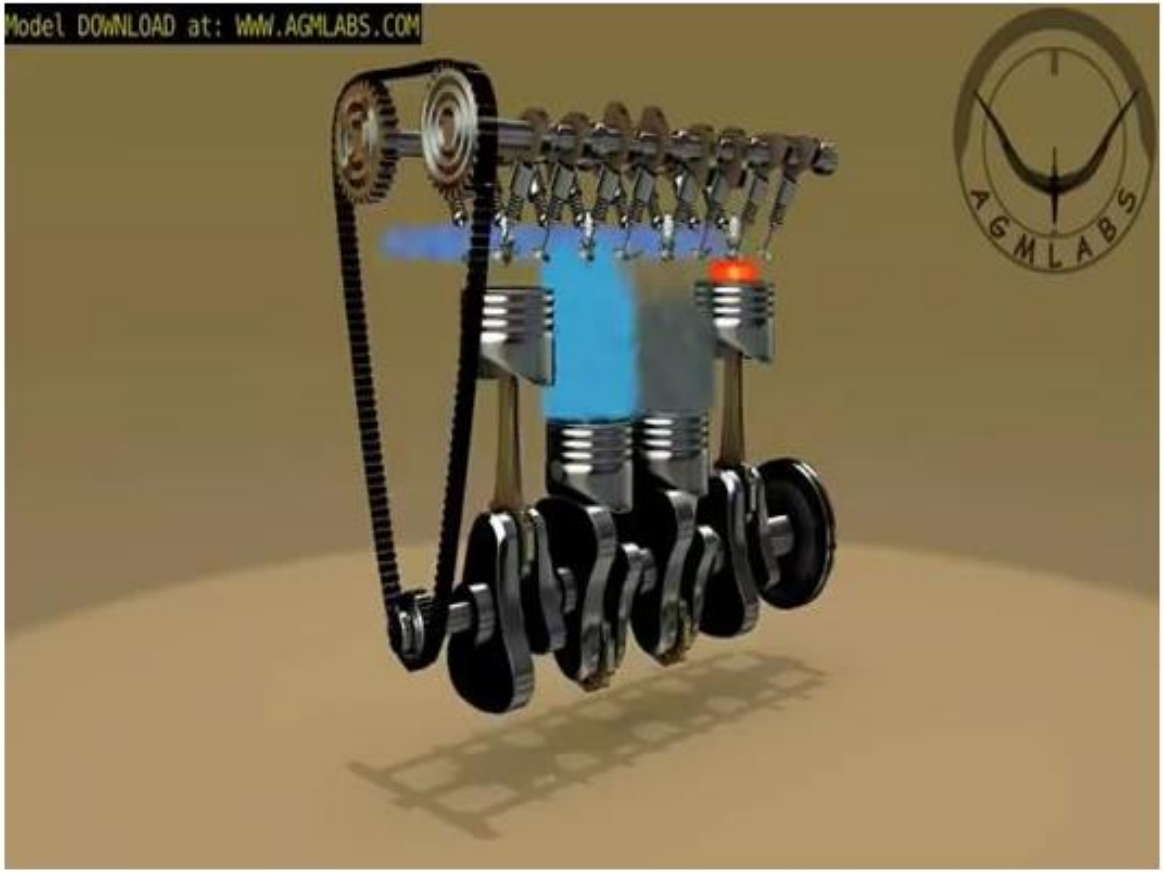
Chemical energy —Combustion→ Thermal energy —Expansion→ Mechanical Energy/ Work

❖Week 02

❑ IC Engine

Combustion / Expansion

Chemical energy → Thermal energy → Mechanical Energy/ Work



Early History

Huygens (1673)	developed piston mechanism
Hautefeuille (1676)	first concept of internal combustion engine
Papin (1695)	first to use steam in piston mechaanism
"Modern" engines	using same principles of operation as present engines – previously no compression cycle
Lenoir (1860)	driving the piston by the expansion of burning products - first practical engine, 0.5 HP later 4.5 kW engines with mech efficiency up to 5%
Rochas (1862)	four-stroke concept was proposed
Otto – Langen (1867)	produced various engine improved efficiency to 11%
Otto (1876)	Four-stroke engine prototype built, 8 HP and patented
Clark (1878)	Two-stroke engine was developed
Diesel (1892)	Single cylinder, compression ignition engine
Daimler/Maybach (1882)	Incorporated IC engine in automobile

❑ Early History of IC Engine

Circa	Event	People and key concept
1860	Rudimentary ICE	Jean J. Lenoir. — Key concept: Combustion increases temperature and gas expands. Expanding gas drives piston to produce mechanical energy. — Modified steam energy; no compression — Operated at 10 cycles/min; efficiency <5% because of low effective compression ratio Sold 500 of them
1867	Atmospheric free piston engine	Nicolaus Otto and Eugene Langen — Key concept: still no compression, but use the inertia of a heavy piston to over-expand the combustion gas to below atmosphere, thereby increasing the expansion ratio. Output mechanical work stored as gravitational potential energy in heavy piston first, and then extracted by clutching piston to fly wheel on downward stroke. — Larger expansion ratio: efficiency increased to 11% — Operate at 28 cycles/minute — Used a flame ignitor through a sliding window Sold 5000, dominated market for 10 years until introduction of the 4-stroke engine
1876	4-stroke engine	Nicolaus Otto
1878	2-stroke engine	Dougald Clerk
1892	Compression Ignition 4-stroke	Rudolf Diesel — Key concepts: prevent the very rapid and high pressure heat

❑ Early History of IC Engine

		process via introducing fuel late in the cycle; compression ignition — Concept developed by the company MAN — Diesel was in heavy debt, and jumped off a ship.
1870's	Development of the Petroleum Industry	
1900's	Spark plug dominated the market of ignition devices	Spark plug was invented by Edmond Berger in 1839. Albert Champion was the most successful manufacturer.
1920's	ICE dominated the market of automotive power plant	Main reason for not using the steam engine for vehicles was that too much water was needed.
1920's	Tetra-ethyl lead as anti-knock agent	Thomas Midgley, under the direction of Carles Kettering at GM found the compound to suppress knock after extensive search. With leaded gasoline, maximum compression ratio was raised from 5 to 9, and engine efficiency increased substantially
1920-1960	Steady development	
1960's	Vehicle emissions became an issue	Smog mechanism was discovered by Haagen Smit
1970's	Oil embargo; energy crisis	
1980's	Start of global competition	
1980's	Catalytic converter and unleaded gasoline	The 3 way catalyst reduced emissions of CO, HC and NOx by more than an order of magnitude, and was the enabler for the vehicles to meet emissions regulations
1990's	Recognition of importance of green house gas	
2000's	Towards sustainable transportation	

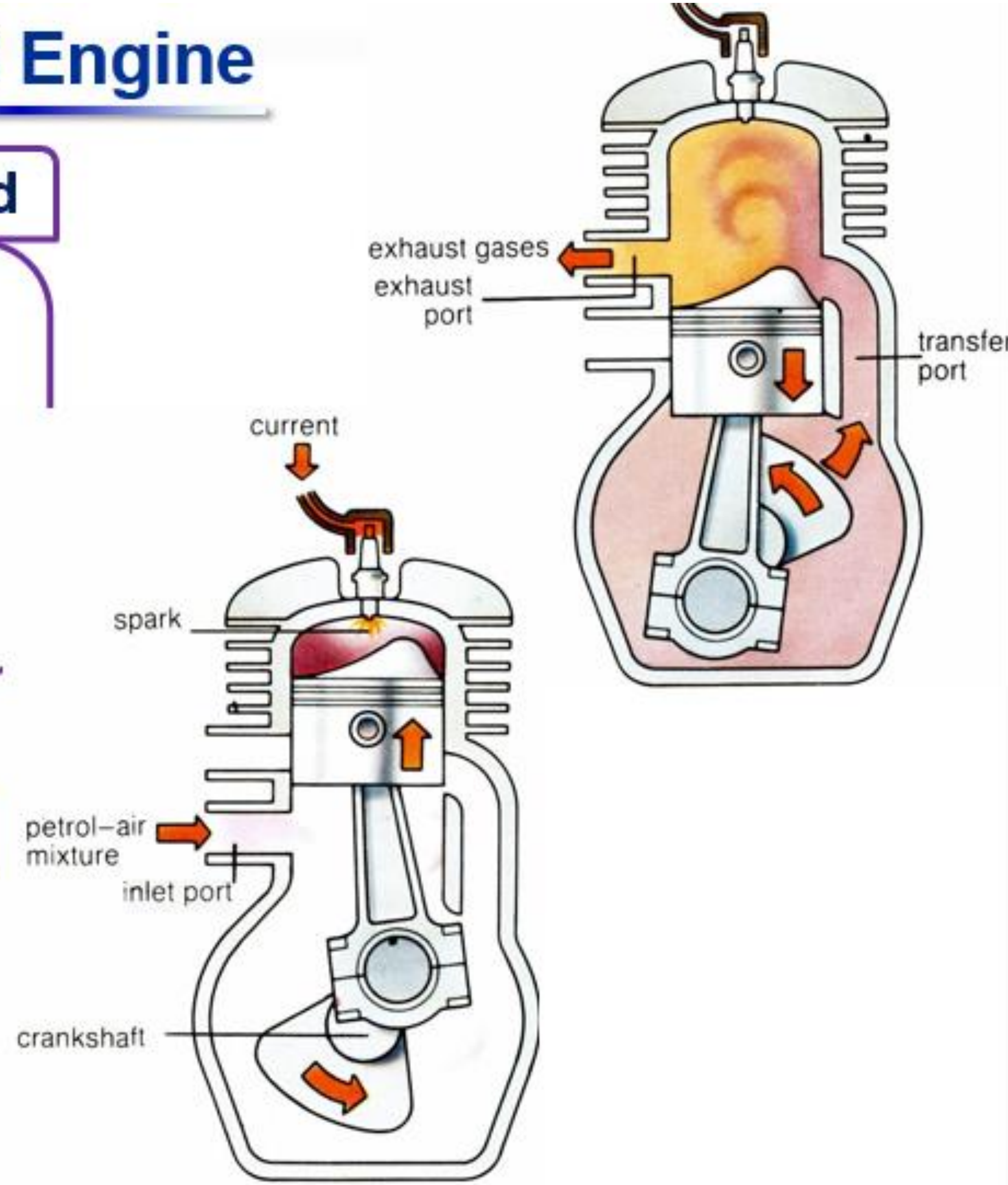
❑ Classification of IC Engine

According to type of fuel used

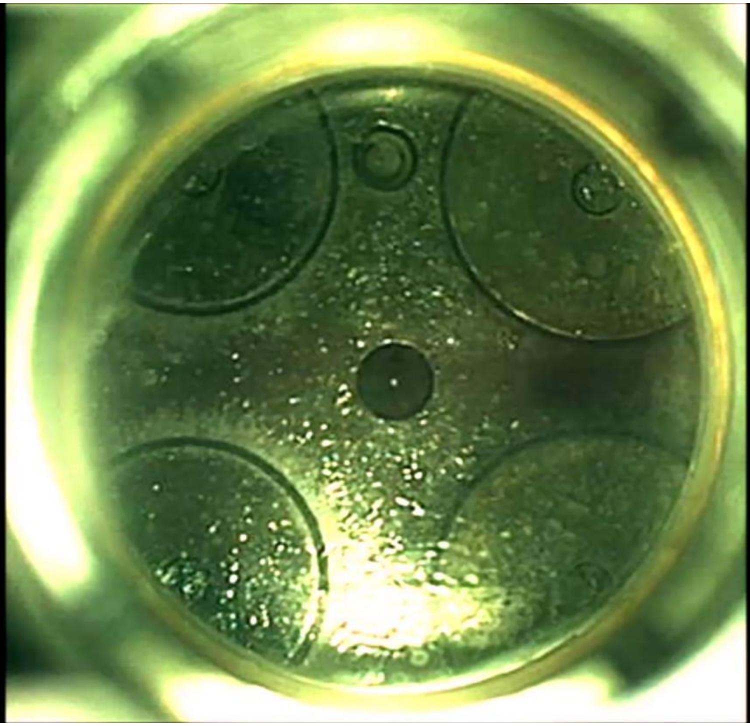
- ✓ Petrol engine
- ✓ Diesel engine
- ✓ Gas engine (CNG, LPG)
- ✓ Dual-fuel engine
- ✓ Hydrogen engine
- ✓ Bio-fuel engine

Number of strokes/cycle

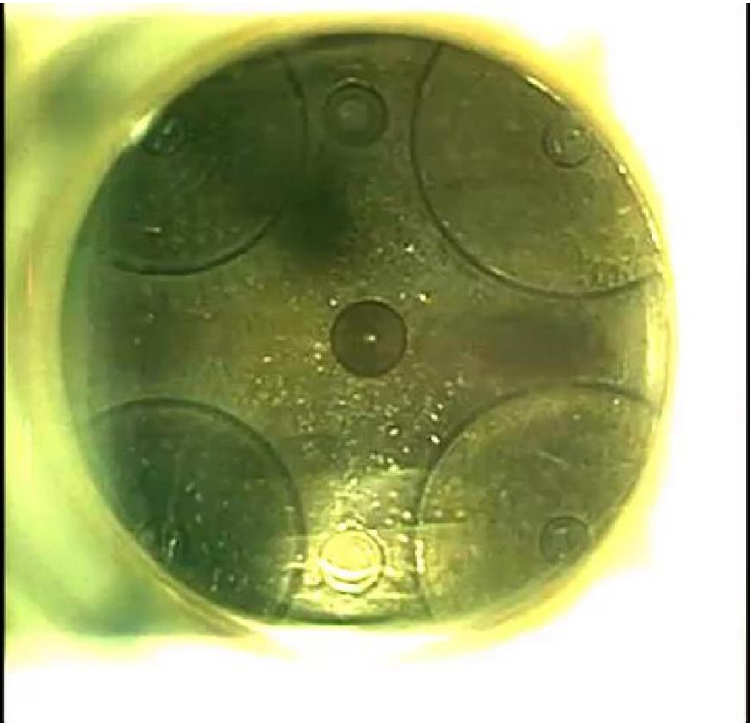
- ✓ Two-stroke cycle
- ✓ Four-stroke cycle



Promotion of normal combustion to PREMIER Combustion



θ_{inj}=4°BTDC single
m_{inj}=0.6mg/cycle



θ_{inj}=6°BTDC/TDC split
m_{inj}=0.3/0.3mg/cycle

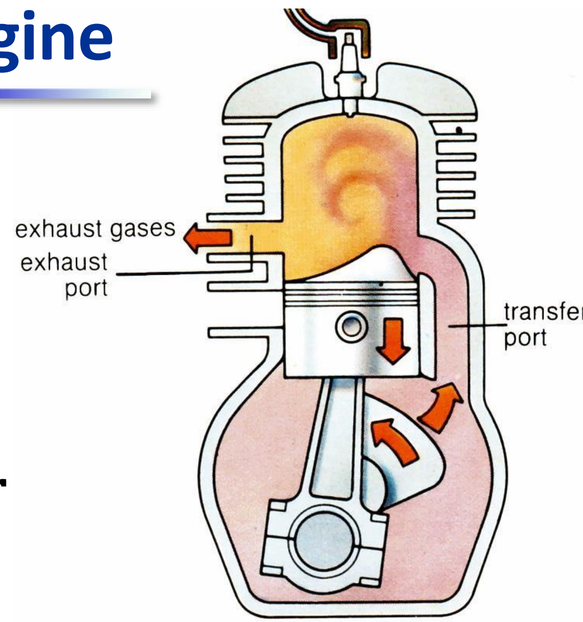
❖Week 03

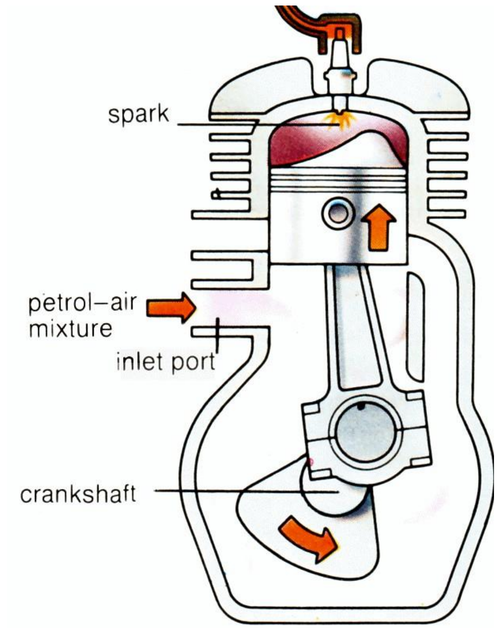
Two-stroke Engine

❑ Classification of IC Engine

Number of strokes/cycle

- ✓ Two-stroke cycle
- ✓ Four-stroke cycle



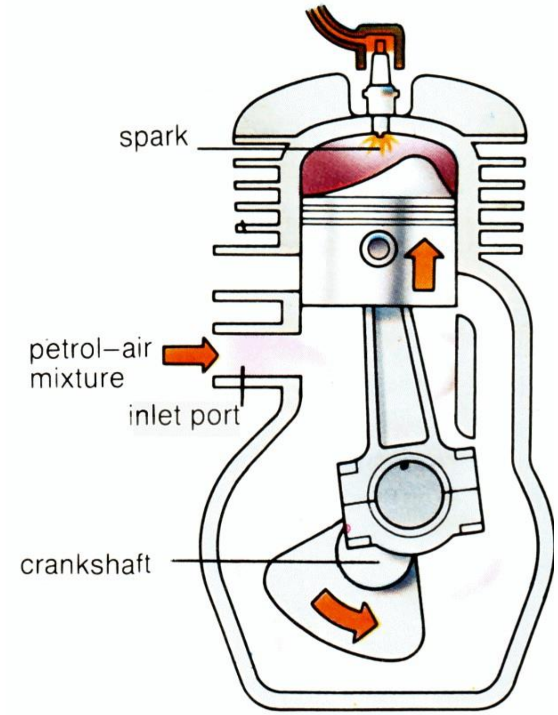


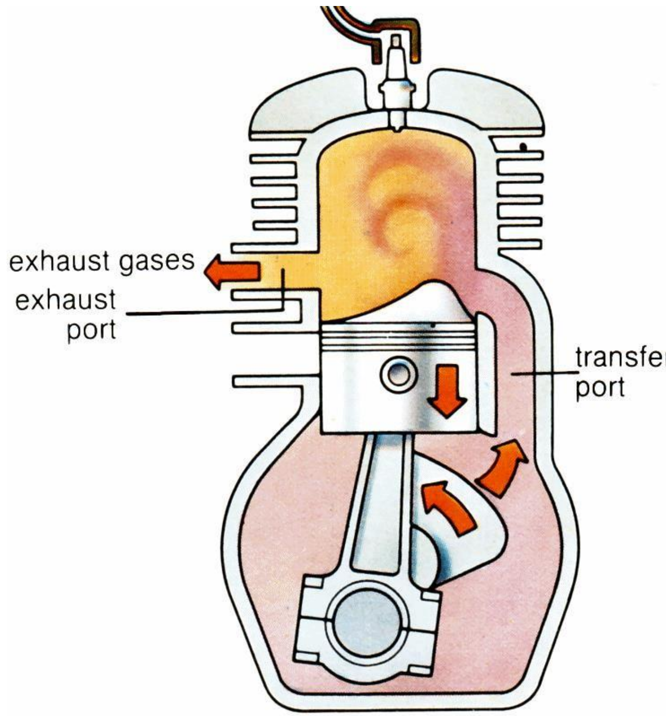
- ✓ **Simplicity in design: cheaper**
- ✓ **Uniform torque on camshaft**
- ✓ **Greater cooling and lubrication requirements**
- ✓ **In SI engine: high fuel consumption; emission, low load/speed**

- ✓ **Theoretically: Develops twice the power of a comparable four stroke engine**
- ✓ **Actually: Effective stroke is reduced; and**
- ✓ **Due to increased heating caused by more power strokes, speed is kept less than four stroke engine**

Two-stroke Engine

Scavenging is the removal of exhaust gases by blowing in fresh air

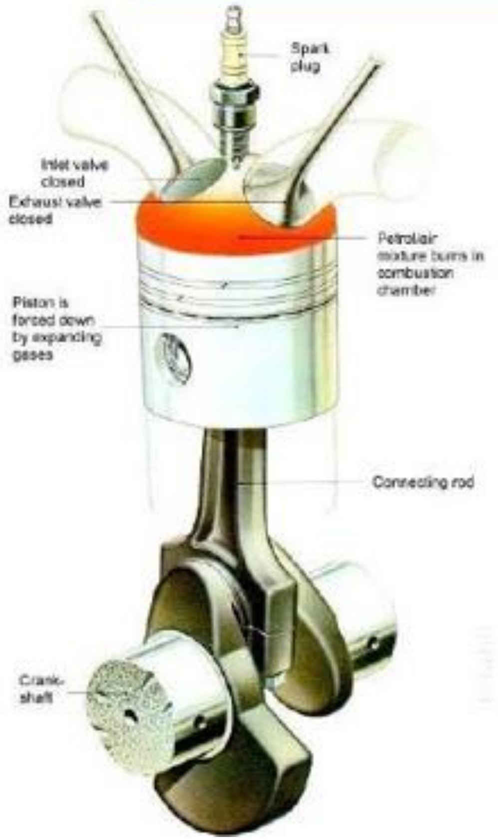


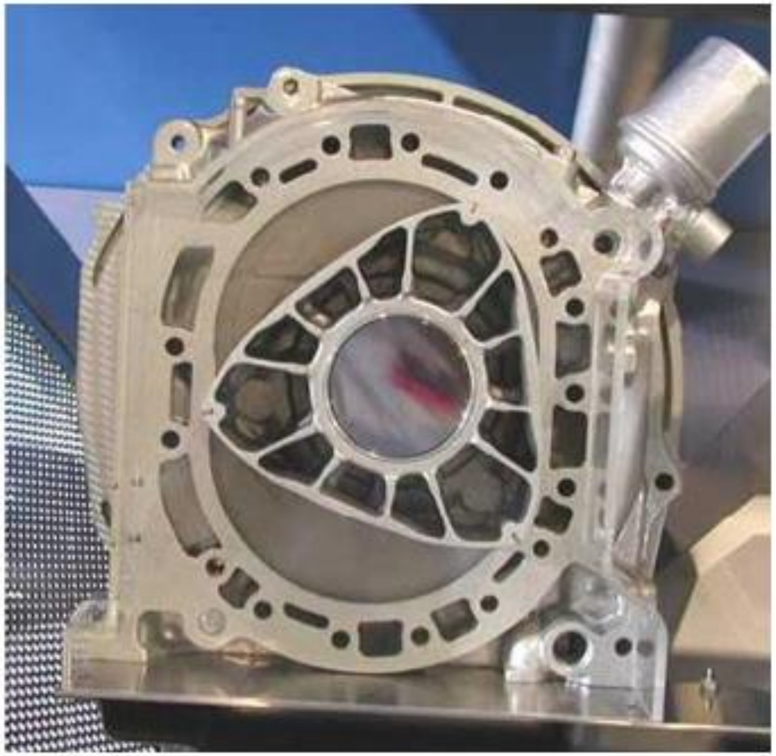


- ✓ **No exhaust stroke; short duration**
- ✓ **Poor scavenging: low mean indicated pressure, incomplete combustion, higher sfc**
- ✓ **Higher mean temperature and greater thermal stress on walls**
- ✓ **Contamination of lubricating oil: wear of piston and cylinder liner**

Basic engine design

- ✓ **Reciprocating engines**
  (subdivided by arrangement of cylinders: in-line, V, radial, opposed piston),
- ✓ **Rotary engines (Wankel and other geometries)**





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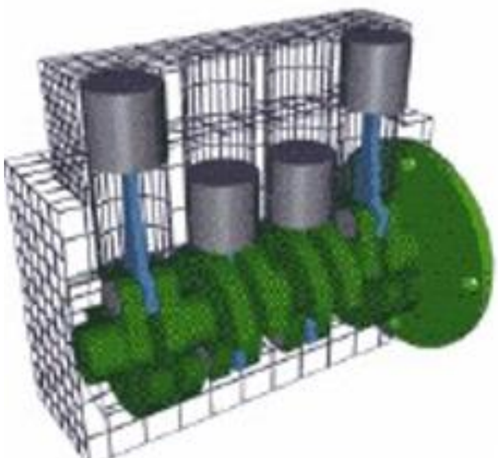
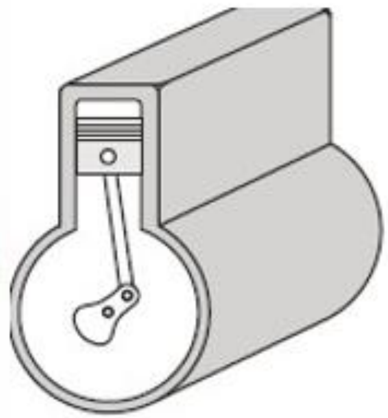
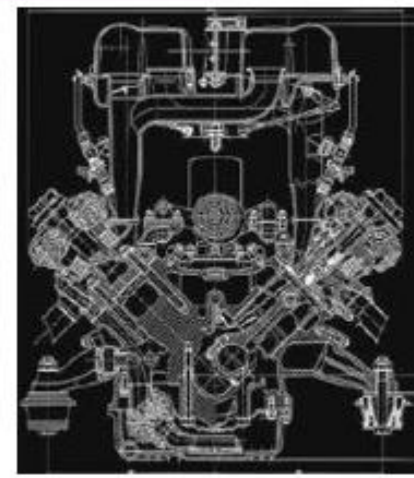
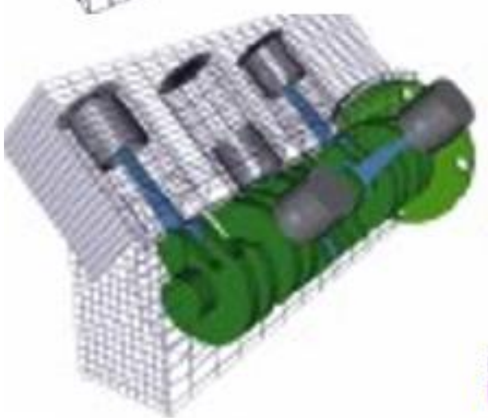
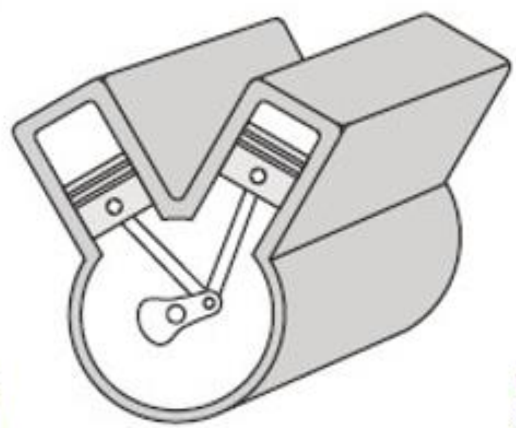
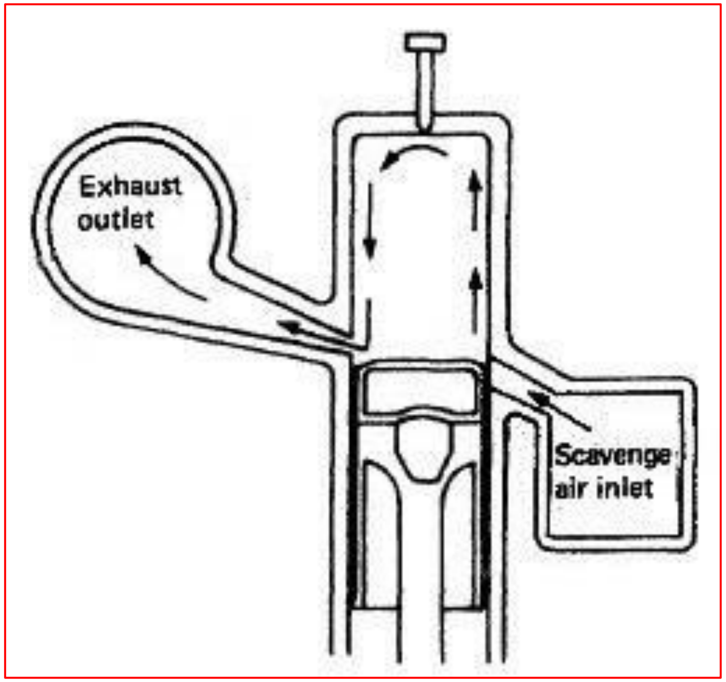



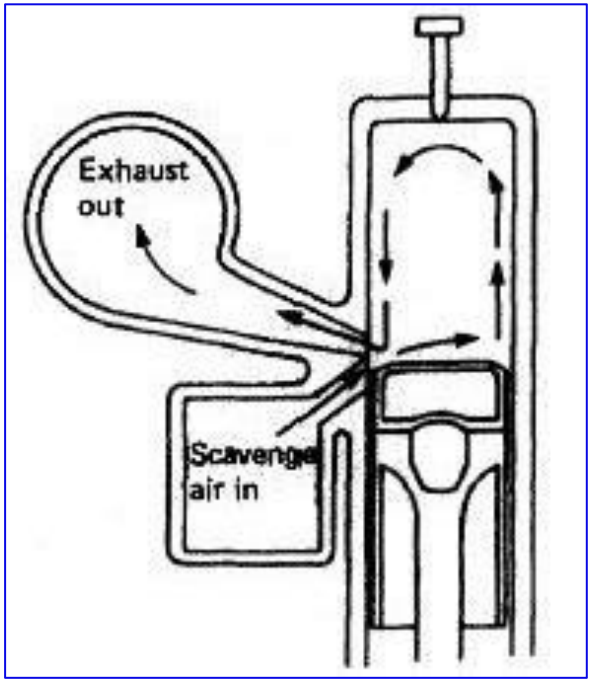




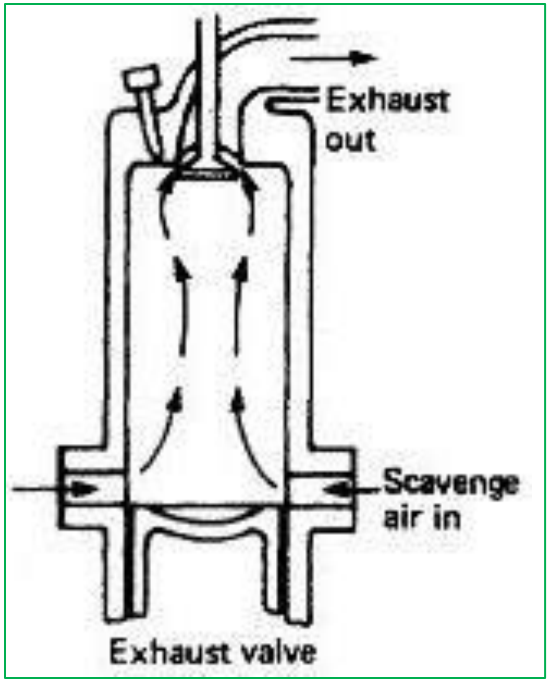

❖Week 04

Two-stroke Engine

- ✓ **Cross-scavenging:** require deflector or inclined ports; poor scavenging of gases near the wall, fresh charge into exhaust port, poor bmep
- ✓ **Loop-scavenging:** flat top piston without deflector, inlet ports on both side of exhaust port, leakage of oil from crankcase to exhaust port
- ✓ **Uniflow scavenging:** absence of mixing of fresh charge with burnt gases, construction simplicity compromised, highest scavenging efficiency

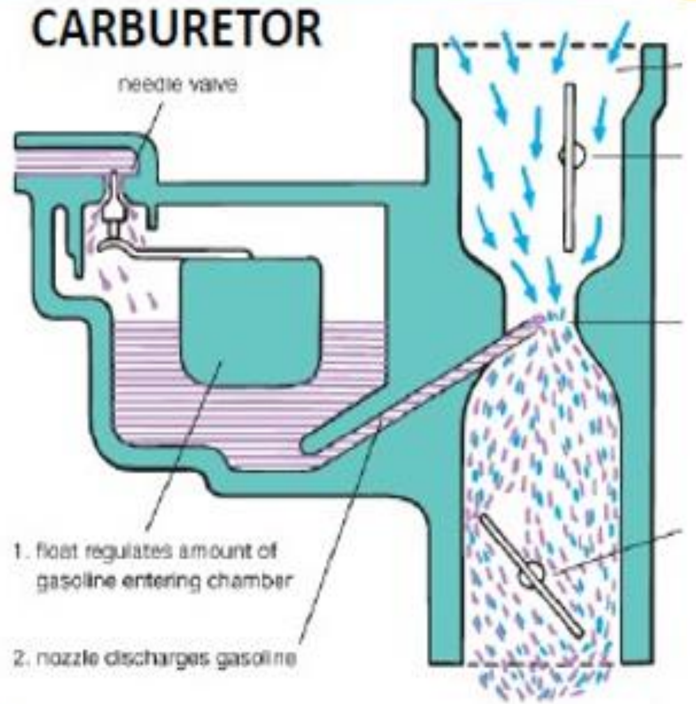


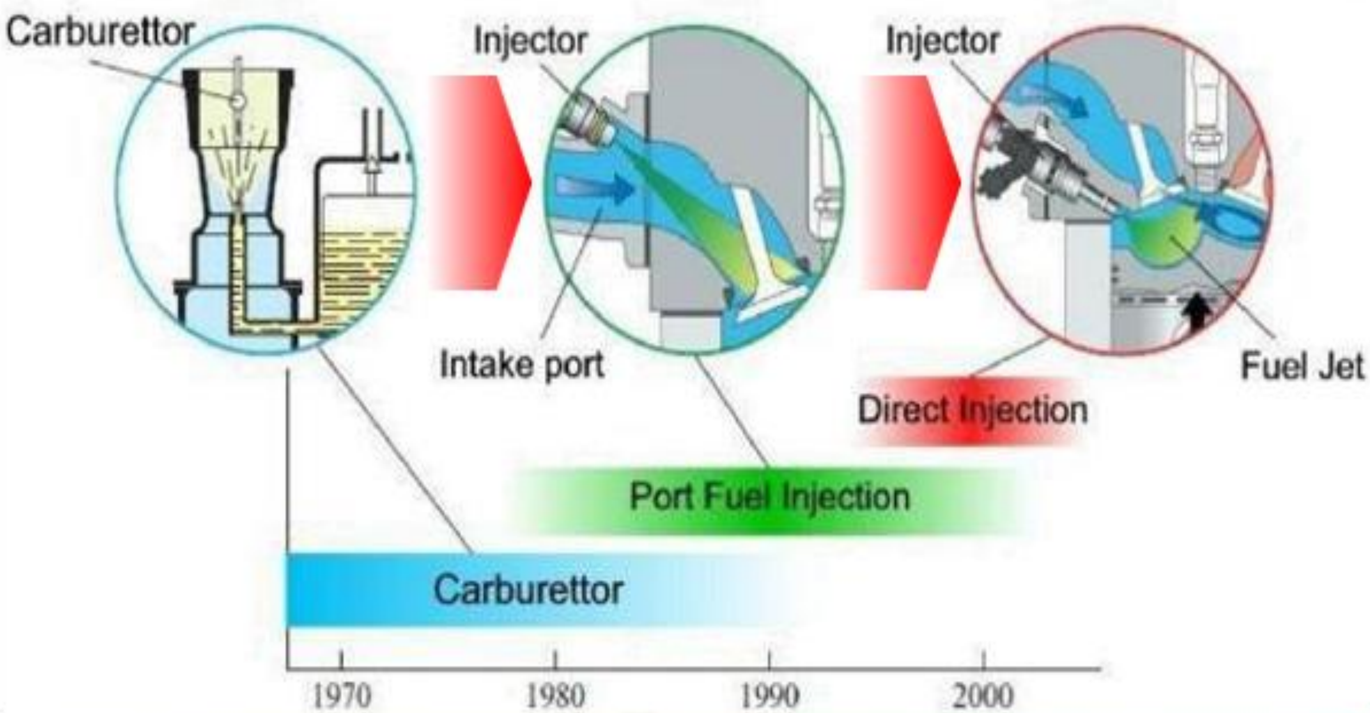




Method of mixture preparation

- ✓ **Carburetion**
- ✓ **fuel injection into the intake ports**
- ✓ **fuel injection into the engine cylinder**





Combustion chamber design

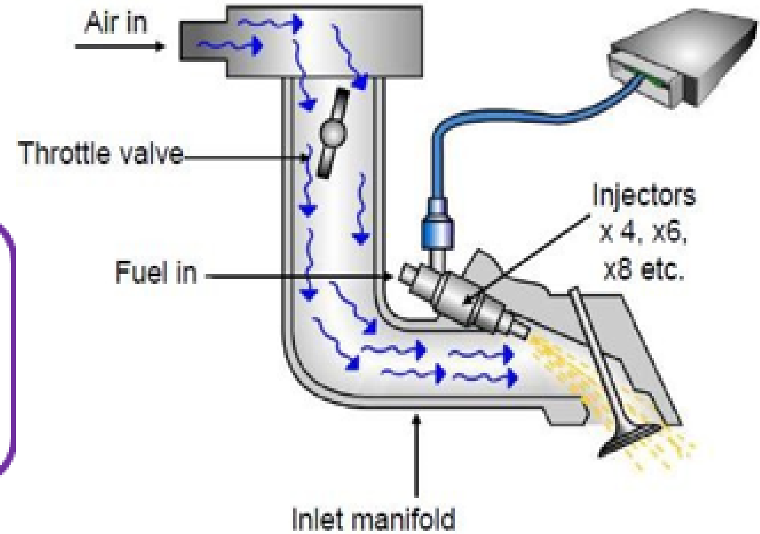
- ✓ Open chamber (wedge, hemisphere, bowl-in-piston)
- ✓ Divided chamber (swirl chambers, prechambers)

Method of ignition

- ✓ Spark ignition
- ✓ Compression ignition (in conventional diesels, as well as ignition in gas engines by pilot injection of fuel oil)

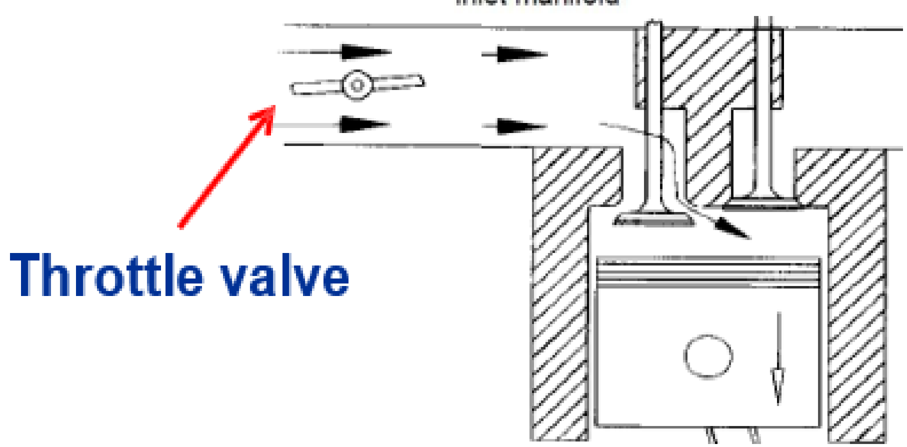
Method of load control

- ✓ Throttling of fuel and air flow together
- ✓ Control of fuel flow alone
- ✓ A combination of these



Method of cooling

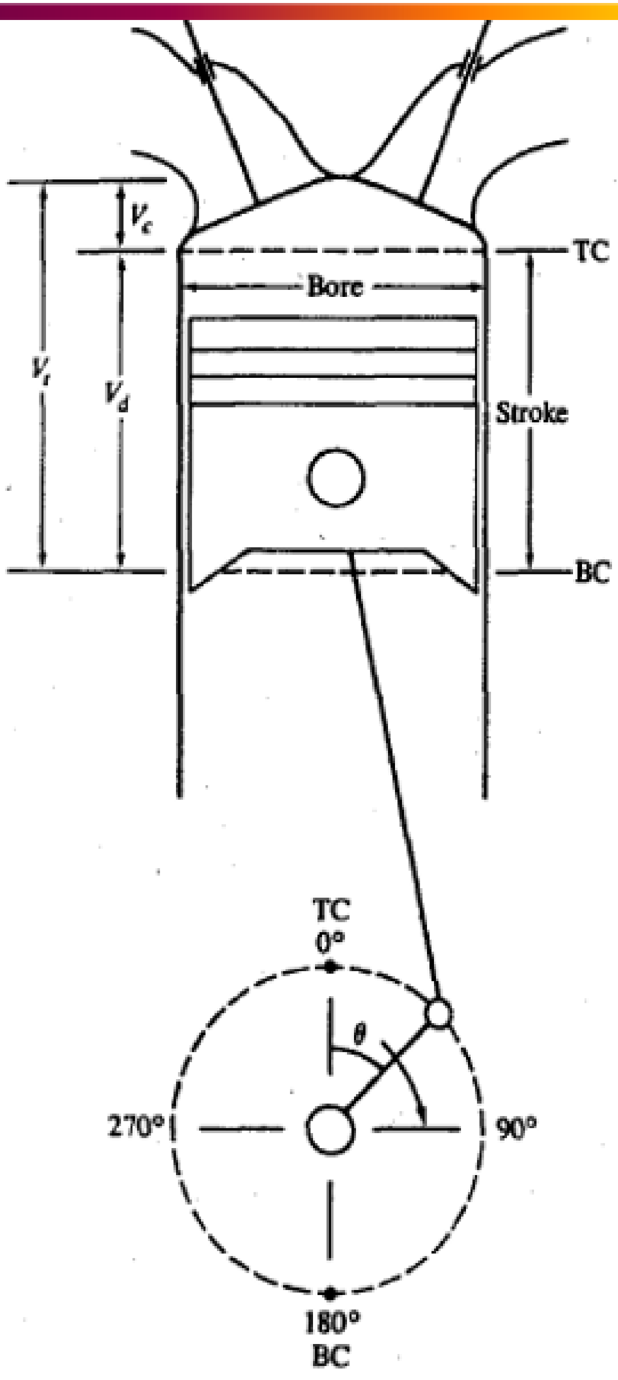
- ✓ Water cooled,
- ✓ Air cooled



Geometrical properties of IC Engine

- Top dead center, TDC
- Bottom dead center, BDC
- Displacement/Swept volume, V_d
- Clearance volume, V_c
- Compression Ratio

$$r_c = \frac{\text{maximum cylinder volume}}{\text{minimum cylinder volume}} = \frac{V_d + V_c}{V_c}$$



Geometrical Properties IC engine

- ✓ Bore
- ✓ Stroke
- ✓ TDC
- ✓ BDC

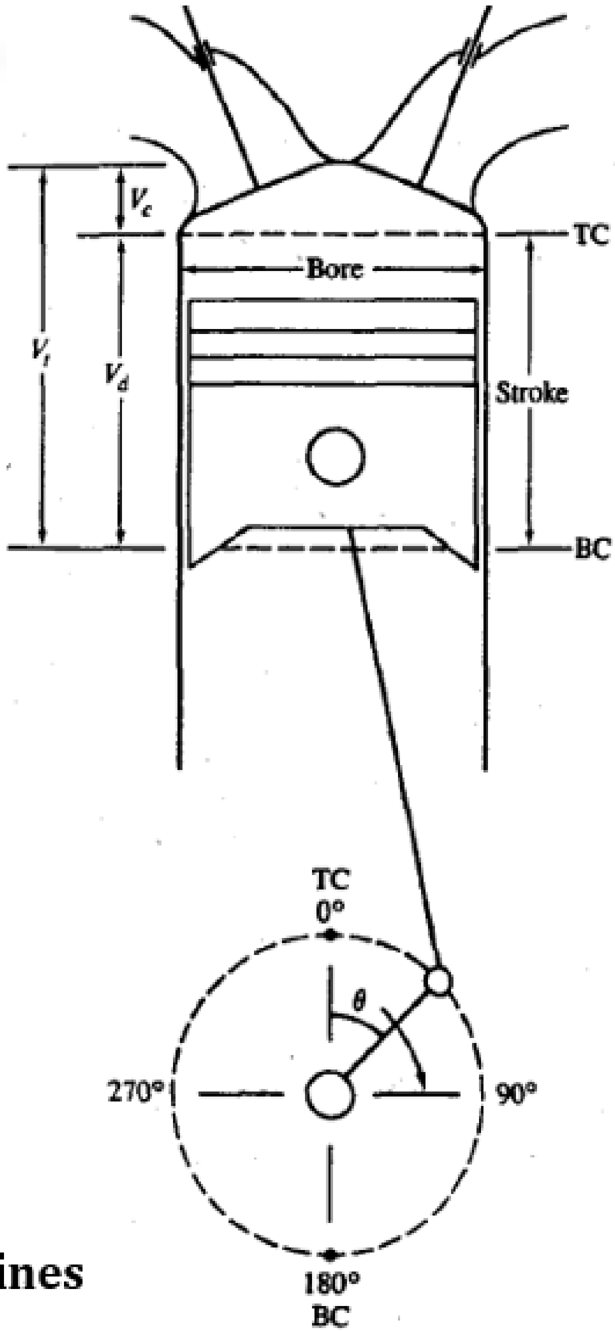
✓ The volume swept out by the piston, while moving from TDC to BDC, or vice versa, is called the displaced or swept volume V_d

✓ The minimum cylinder volume is called the clearance volume V_c

✓ Compression ratio, r_c :

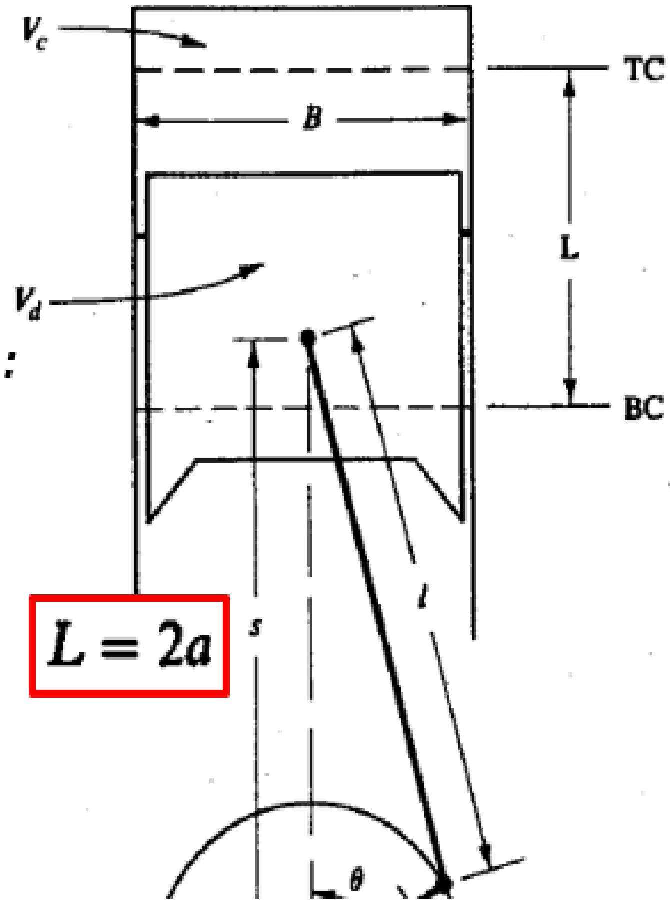
$$r_c = \frac{\text{maximum cylinder volume}}{\text{minimum cylinder volume}} = \frac{V_d + V_c}{V_c}$$

r_c = 8 to 12 for SI engines and r_c = 13 to 26 for CI engines



❑ Geometrical Properties IC engine

✓ B = bore, L = stroke, l = connecting rodd length, a = crank radius, θ = crank angle, s = distance between the crank axis and the piston pin axis



✓ The cylinder volume V at any crank position θ is :

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

$$L = 2a$$

✓ An important characteristic speed is the mean piston speed :

$$\bar{S}_p = 2LN$$

✓ Since the piston travels a distance of twice the stroke per revolution.

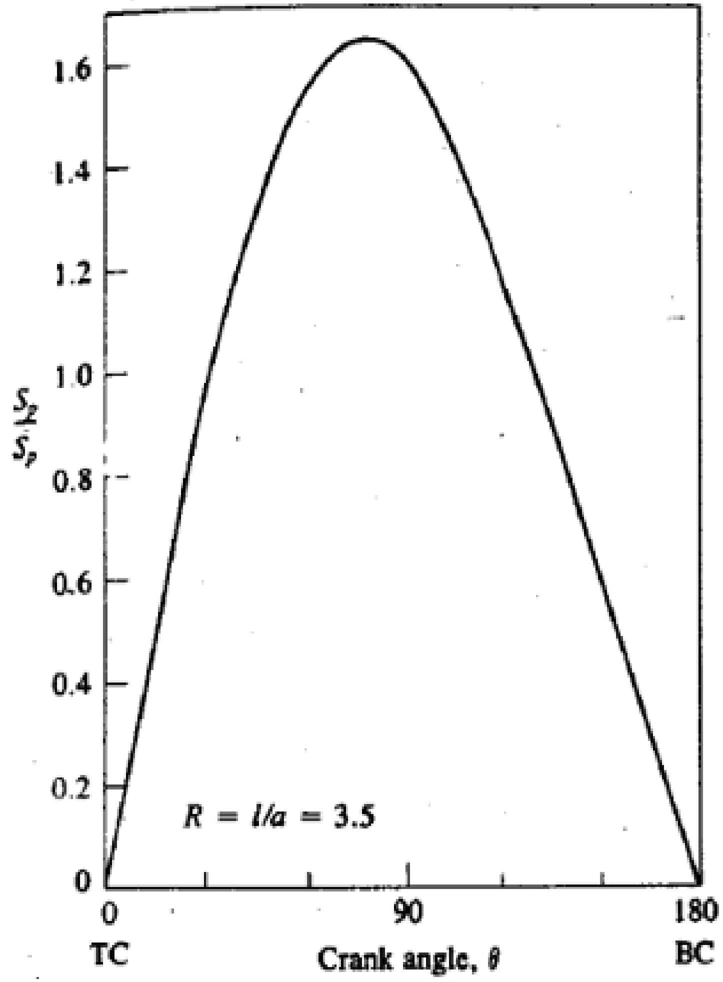
✓ The mean piston speed is an important parameter in engine design since stresses and other factors scale with piston speed rather than with engine speed.

✓ An important characteristic speed is the mean piston speed :

$$\bar{S}_p = 2LN$$

✓ Gas flow velocities in the intake and the cylinder all scale with the mean piston speed.

✓ The piston velocity is zero at the beginning of the stroke, reaches a maximum near the middle of the stroke, and decreases to zero at the end of the stroke.



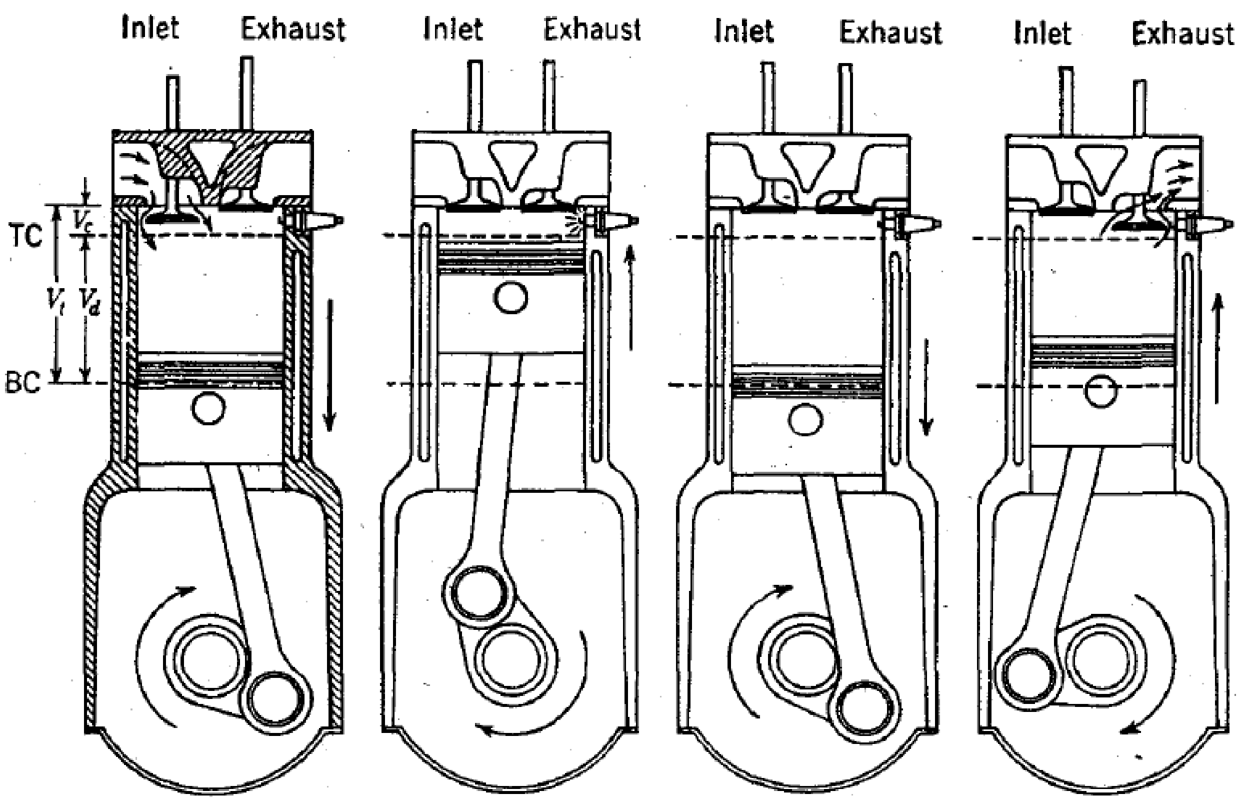
✓ Maximum mean piston speed range within the 8 to 15 m/s (1500 to 3000 ft/min).

✓ Automobile engines operate at the higher end of this range; the lower end is typical of large marine diesel engines

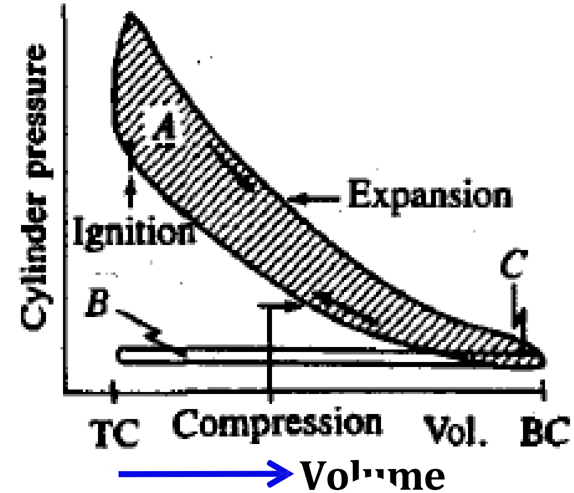
❖Week 04

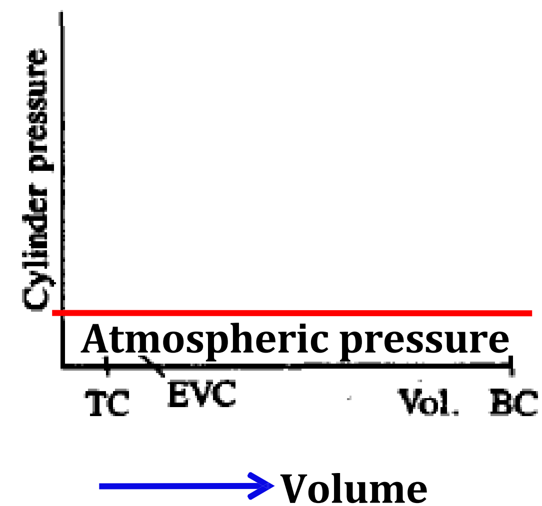
ENGINE PERFORMANCE PARAMETERS

✓ **The cylinder pressure and corresponding cylinder volume throughout the engine cycle can be plotted on a p-V diagram.**



(a) Intake (b) Compression (c) Expansion (d) Exhaust



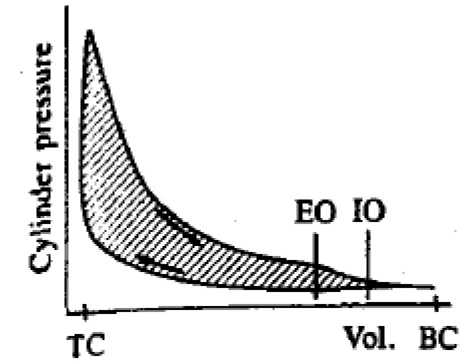


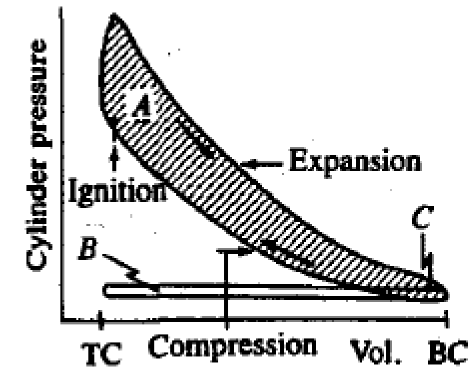
ENGINE PERFORMANCE PARAMETERS

❑ Indicated Work per cycle ($W_{i,c}$)

✓ indicated work is the work transferred from the gas to the piston during a cycle, is obtained by integrating around the curve to obtain the area enclosed on the diagram:

$$W_{c,i} = \oint p \, dV$$

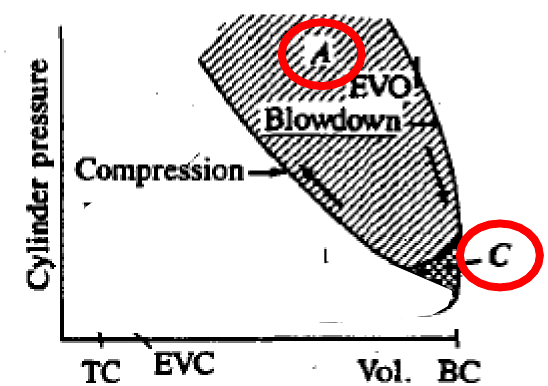




➢ Gross indicated work per cycle ($W_{c,ig}$)

✓ The Work delivered to the piston over the compression and expansion strokes only

$$W_{c,ig} = \text{area } A + \text{area } C$$



(c)

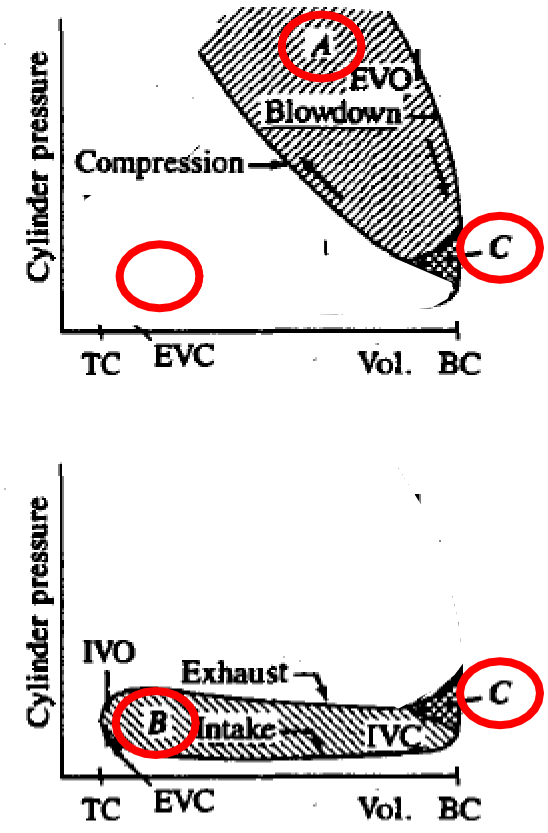
ENGINE PERFORMANCE PARAMETERS

- **Net indicated work per cycle ($W_{c,in}$)**

✓ **The Work delivered to the piston over the entire four-stroke cycle**

$$W_{c,in} = (\text{area } A + \text{area } C) - (\text{area } B + \text{area } C)$$

$$W_{c,in} = W_{c,ig} - W_p$$



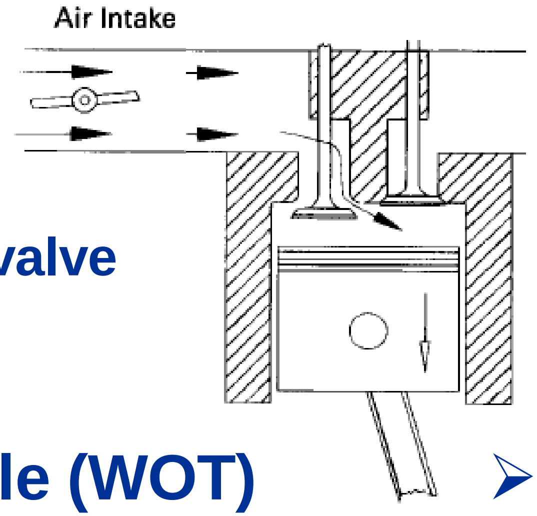
(c)

- **Pumping work per cycle (W_p)**

✓ **Work transfer between the piston and the cylinder gases during the inlet and exhaust strokes**

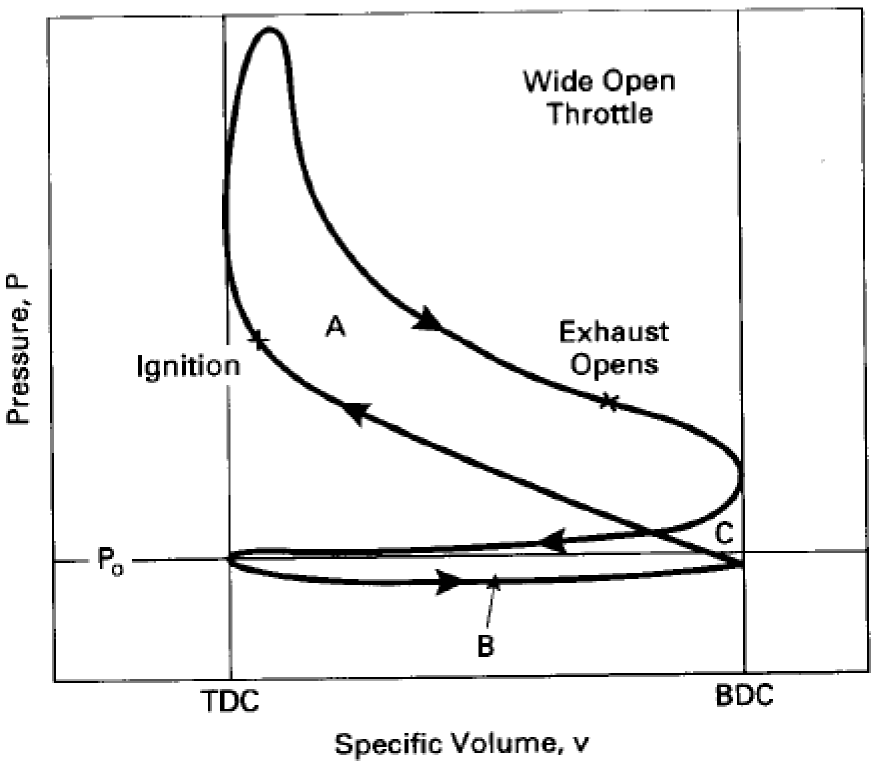
✓ **Work transfer will be to the cylinder gases if the pressure during the intake stroke is lower than the pressure during the exhaust stroke. Ex: Naturally aspirated engine**

✓ **Turbocharged engine : ?????**

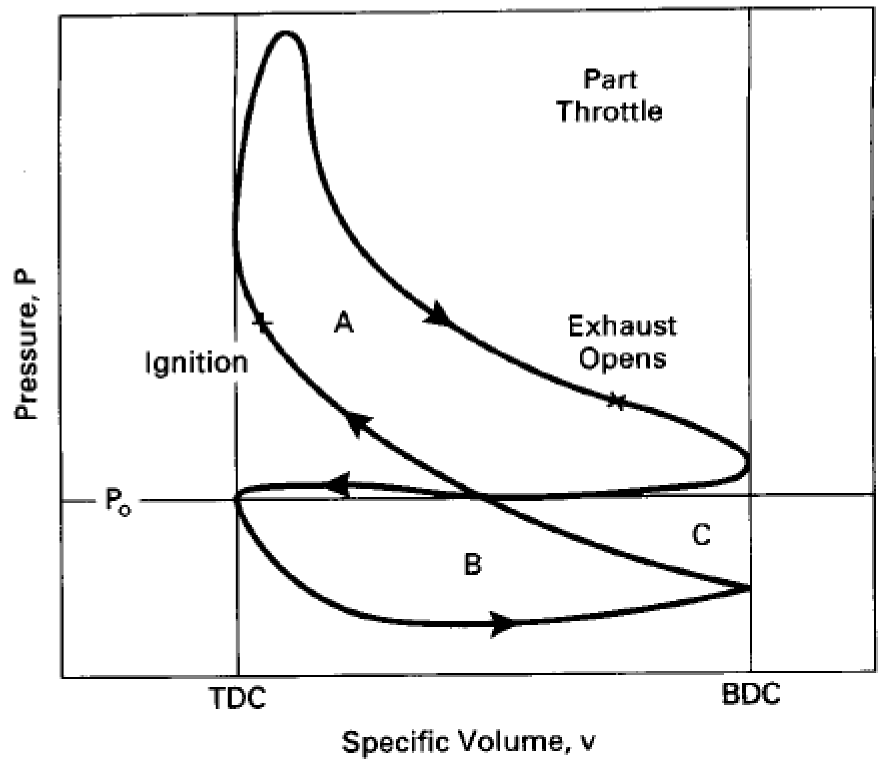


Throttle valve

- **Wide Open Throttle (WOT)**
- **Part Throttle**



(a)



(b)

❖Week 06

ENGINE PERFORMANCE PARAMETERS

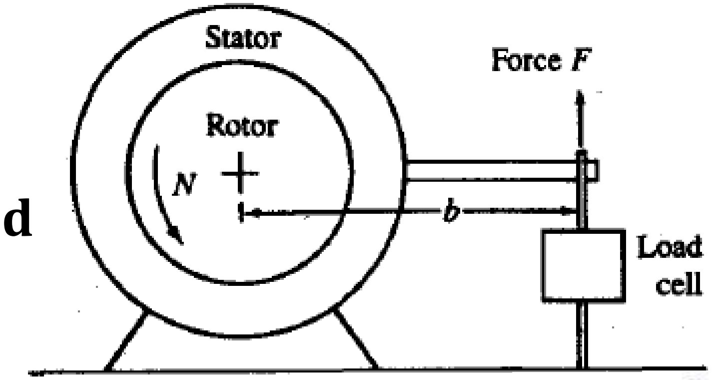
❑ Brake Power, P_b

The power P_b delivered by the engine and absorbed by the dynamometer is the product of torque and angular speed:

$$P = 2\pi N T$$

where N is the crankshaft rotational speed

$$T = Fb$$



- **Torque is a measure of an engine's ability to do work**
- **Power is the rate at which work is done.**

ENGINE PERFORMANCE PARAMETERS

❑ Indicated power (P_i)

✓ The rate of work transfer from the gas within the cylinder to the piston; is related to the indicated work per cycle:

$$P_i = \frac{W_{c,i} N}{n_R}$$

where, For four-stroke cycles, n_R = 2; for two-stroke cycles, n_R = 1; since the four-stroke engine has two revolutions per power stroke.

✓ It differs from the brake power by the power absorbed in overcoming engine friction, driving engine accessories (cooling fan, muffler, and tail pipe etc.), and the pumping power.

✓ All of these power requirements are grouped together and called friction power P_f :

$$P_{ig} = P_b + P_f$$

ENGINE PERFORMANCE PARAMETERS

➢ Mechanical efficiency (η_m)

✓ The ratio of the brake (or useful) power delivered by the engine to the indicated power is called the mechanical efficiency η_m :

$$\eta_m = \frac{P_b}{P_{ig}} = 1 - \frac{P_f}{P_{ig}}$$

✓ It depends on throttle position as well as engine design and engine speed.

✓ Typical values for a modern automotive engine at wide open or full throttle (WOT) are 90 percent at speeds below about 30 to 40 rev/s (1800 to 2400 rev/min), decreasing to 75 percent at maximum rated speed.

✓ As the engine is throttled, mechanical efficiency decreases, eventually to zero at idle operation.

ENGINE PERFORMANCE PARAMETERS

❑ Mean Effective Pressure (*mep*)

✓ The work done per unit displacement volume, and has units of force/area :

$$P_i = \frac{W_{c,i}\, N}{n_R} \quad \longrightarrow \quad \text{Work per cycle} = \frac{P n_R}{N}$$

$$\text{mep} = \frac{P n_R}{V_d N}$$

$$\text{mep(kPa)} = \frac{P(\text{kW})\, n_R \times 10^3}{V_d(\text{dm}^3)\, N(\text{rev/s})}$$

$$\text{mep(kPa)} = \frac{6.28\, n_R\, T(\text{N}\cdot\text{m})}{V_d(\text{dm}^3)}$$

✓ it scales out the effect of engine size, allowing performance comparison of engines of different displacement.

ENGINE PERFORMANCE PARAMETERS

➢ Indicated mean effective pressure (*imep*)

✓ the net work per unit displacement volume done by the gas during compression and expansion.

$$imep = bmep + fmep$$

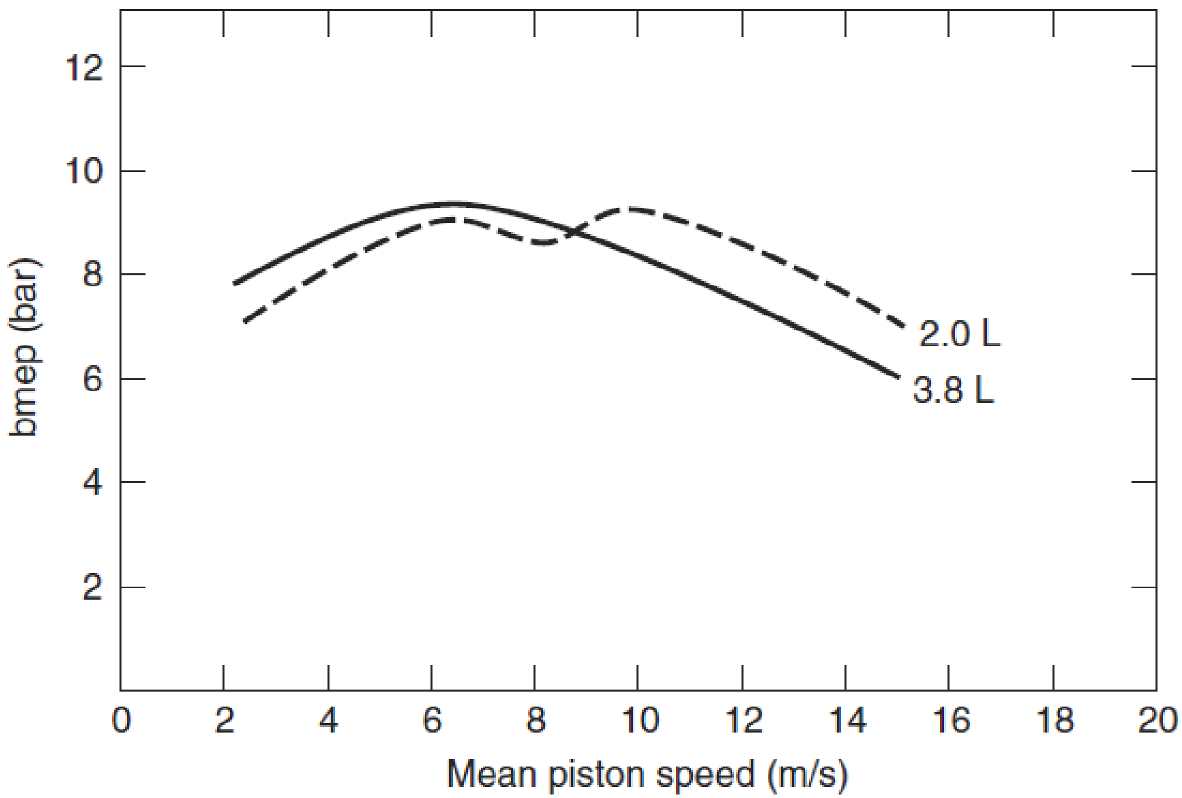
➢ Brake mean effective pressure (*bmep*)

✓ the external shaft work per unit volume done by the engine.

➢ Friction mean effective pressure (*fmep*)

✓ The friction mean effective pressure (*fmep*) includes the mechanical engine friction, the pumping losses during the intake and exhaust strokes, and the work to run auxiliary components such as oil and water pumps.

ENGINE PERFORMANCE PARAMETERS



Reference:

✓ **Internal Combustion Engines Applied Thermosciences,**

-C. R. Ferguson and Allan T. Kirkpatrick

ENGINE PERFORMANCE PARAMETERS

❑ Specific Fuel Consumption (*sfc*)

Fuel consumption rate divided by power

$$sfc = \frac{\dot{m}_f}{P}$$

where, m_f - is mass flow rate of fuel per unit time

✓ **It measures how efficiently an engine is using the fuel supplied to produce work**

✓ **isfc**

✓ **bsfc**

❑ Brake Thermal Efficiency, (η_b)

The ratio of the work produced per cycle to the amount of fuel energy supplied per cycle

$$\eta_f = \frac{P}{\dot{m}_f Q_{HV}} \qquad \eta_f = \frac{1}{sfc\ Q_{HV}}$$

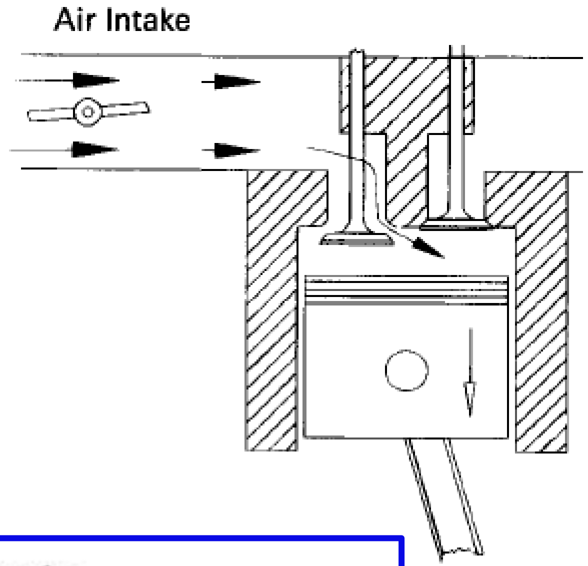
where, Q_{HV} - heating value of a fuel, defines its energy content

ENGINE PERFORMANCE PARAMETERS

❑ Volumetric Efficiency

✓ It measures how efficiently an engine is using the fuel supplied to produce work

✓ defined as the mass of fuel and air inducted into the cylinder divided by the mass that would occupy the displaced volume at the density ρ_i in the intake manifold



$$\eta_v = \frac{\text{mass of air inhaled per cylinder per cycle}}{\text{mass of air to occupy swept volume per cylinder at ambient } p \text{ and } T}$$

✓ The intake system - the air filter, carburetor, and throttle plate (in a spark-ignition engine), intake manifold, intake valve restricts the amount of air which an engine of given displacement can induct

ENGINE PERFORMANCE PARAMETERS

❑ Specific Emissions (SE) and Emissions Index (EI)

✓ **The four main engine exhaust emissions which must be controlled are oxides of nitrogen (NOx), carbon monoxide (CO), hydrocarbons (HC), and solid particulates (part)**

✓ **Specific emissions are the mass flow rate of pollutant per unit power output:**

$$sNO_x = \frac{\dot{m}_{NO_x}}{P}$$

$$sCO = \frac{\dot{m}_{CO}}{P}$$

$$sHC = \frac{\dot{m}_{HC}}{P}$$

$$sPart = \frac{\dot{m}_{part}}{P}$$

✓ **Alternatively, emission rates can be normalized by the fuel flow rate; Emissions index has units of emissions flow per fuel flow:**

$$(EI)_{NOx} = \dot{m}_{NOx}[\text{gm/sec}] / \dot{m}_f[\text{kg/sec}]$$

$$(EI)_{CO} = \dot{m}_{CO}[\text{gm/sec}] / \dot{m}_f[\text{kg/sec}]$$

$$(EI)_{HC} = \dot{m}_{HC}[\text{gm/sec}] / \dot{m}_f[\text{kg/sec}]$$

$$(EI)_{part} = \dot{m}_{part}[\text{gm/sec}] / \dot{m}_f[\text{kg/sec}]$$

❑ Engine Specific Weight and Specific Volume

$$\text{Specific weight} = \frac{\text{engine weight}}{\text{rated power}}$$

$$\text{Specific volume} = \frac{\text{engine volume}}{\text{rated power}}$$

✓ **These parameters are important for engines used in transportation vehicles such as boats, automobiles, and especially airplanes, where keeping weight to a minimum is necessary.**

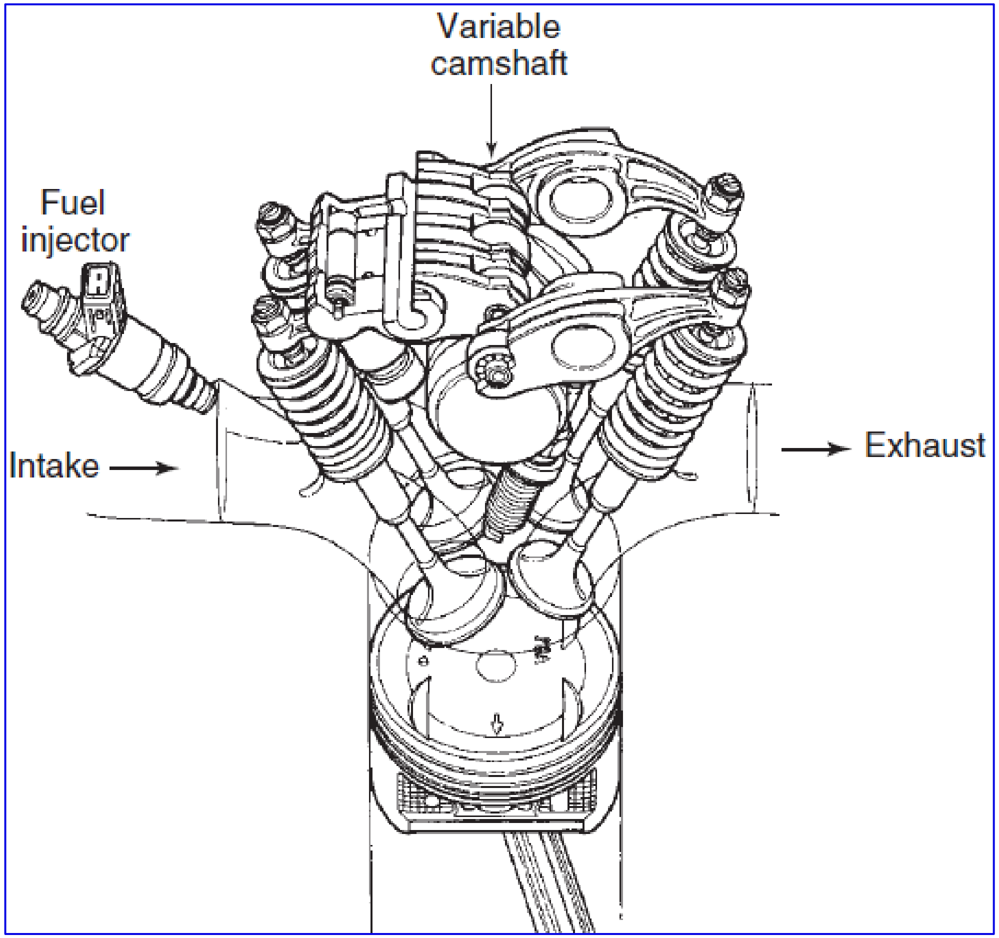
❑ Output Per Displacement (OPD)

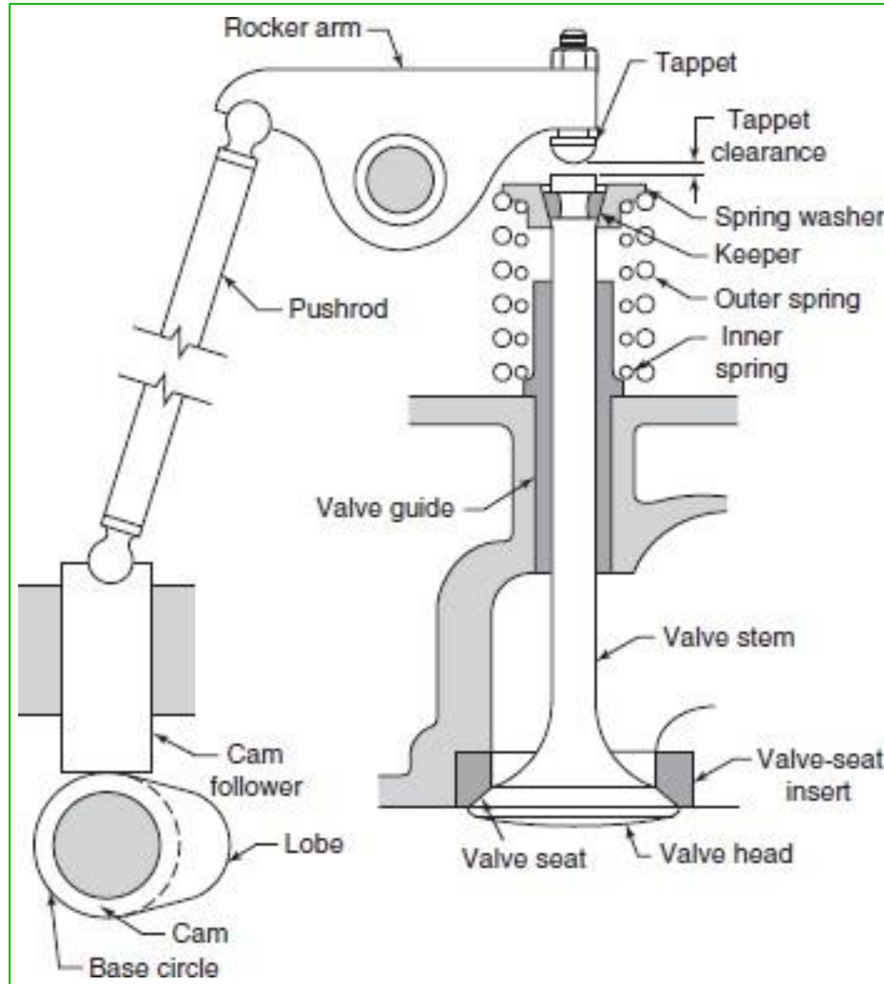
$$\text{output per displacement} \qquad \text{OPD} = \dot{W}_b/V_d$$

✓ **Modern automobile engines usually have brake power output per displacement in the range of 40 to 80 kW/L.**

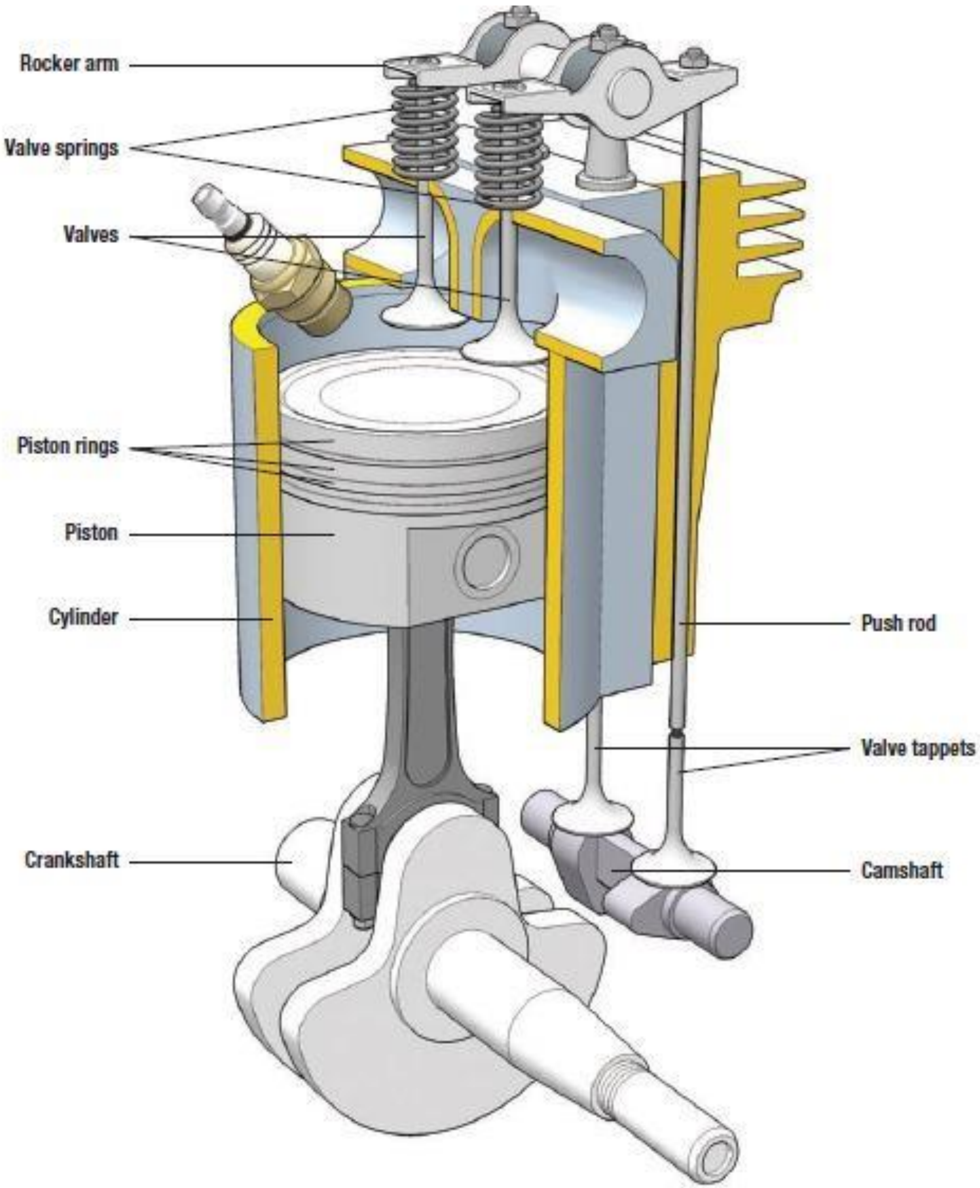
✓ **The Honda eight-valve-per-cylinder V4 motorcycle engine generates about 130 kW/L, an extreme example of a high-performance racing engine.**

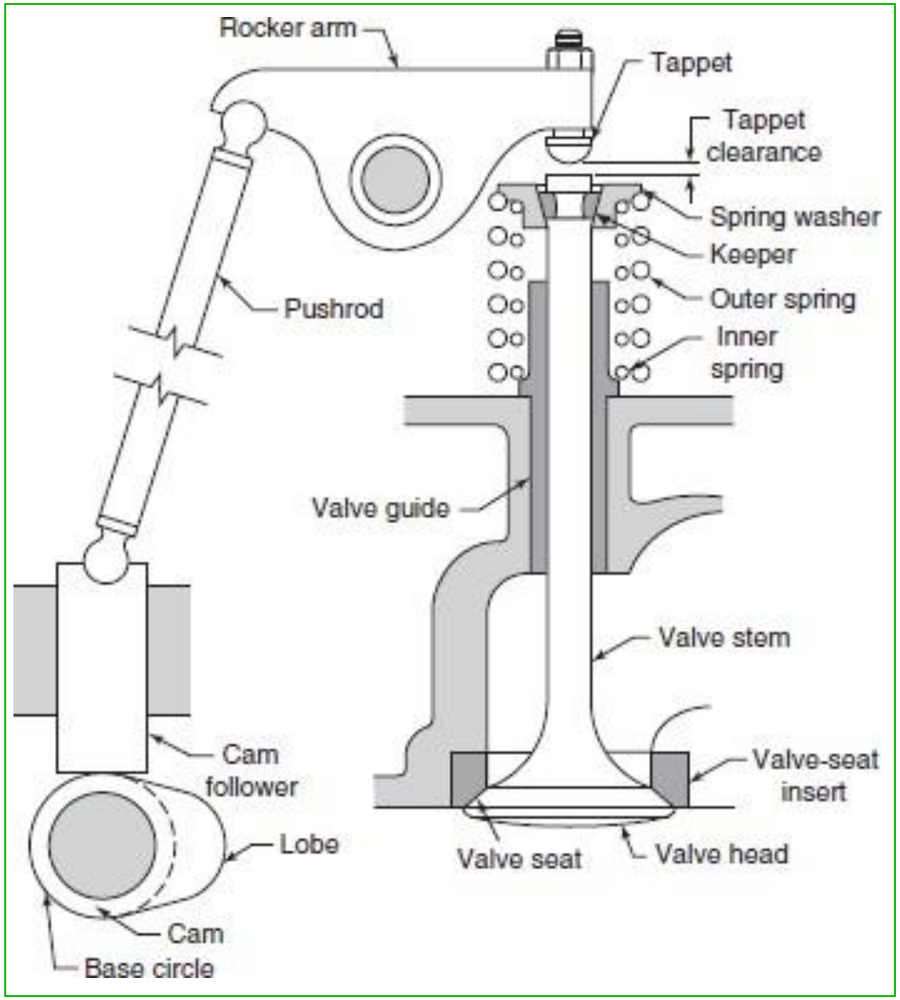
❑ Valve Timing in IC Engine



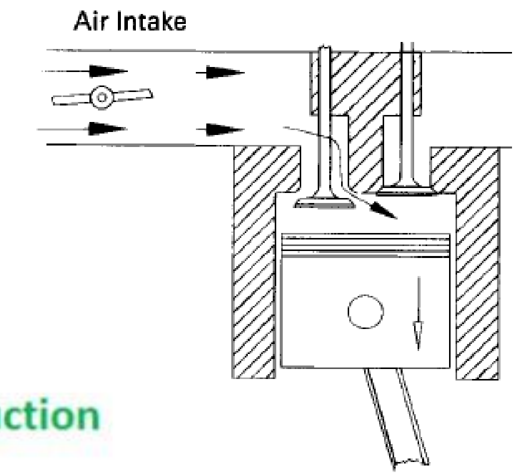


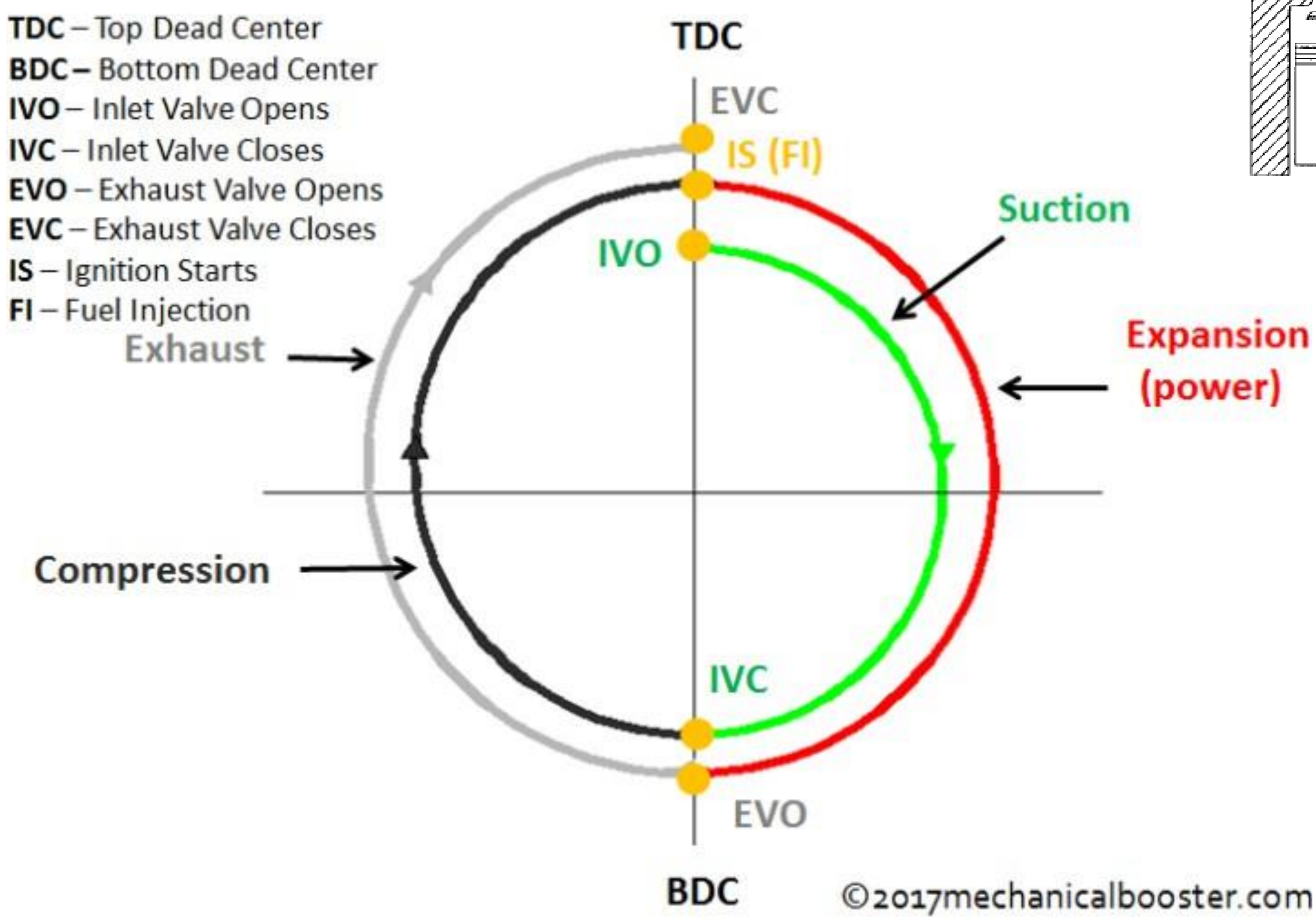
❑ Valve Timing in IC Engine





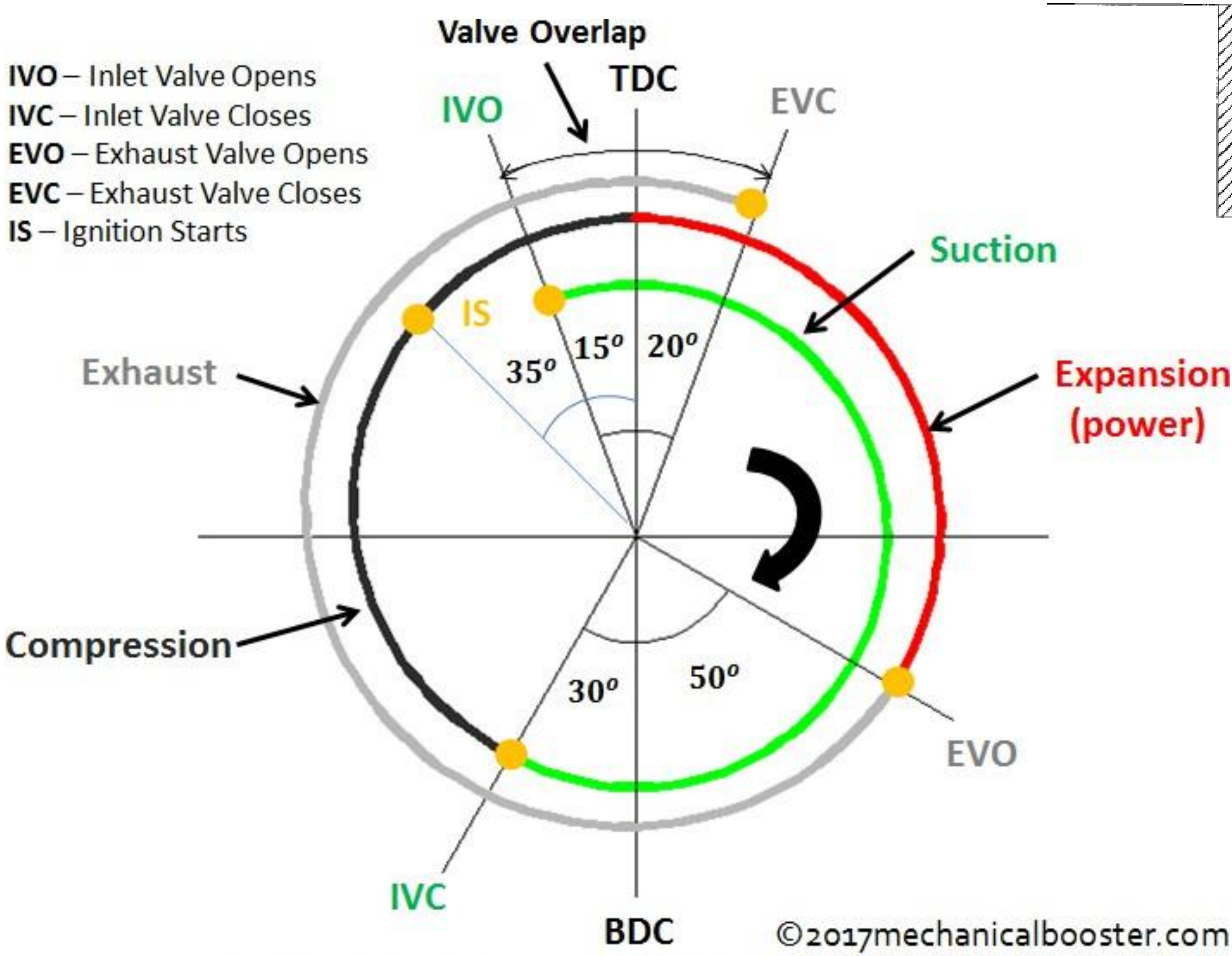
❑ Valve Timing in IC Engine



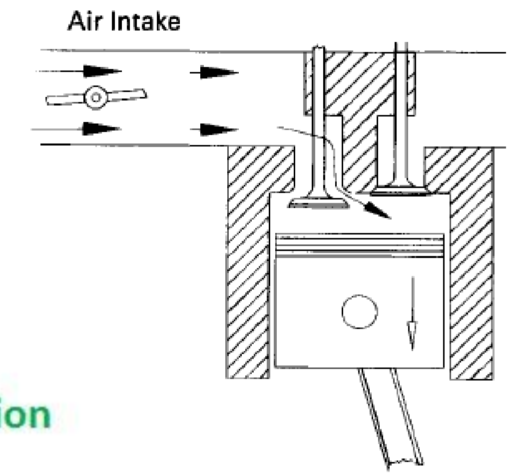


Theoretical Valve Timing Diagram of 4 Stroke Engine

❑ Valve Timing in IC Engine



Valve Timing Diagram of 4 Stroke Petrol Engine



❑ Valve Timing in IC Engine

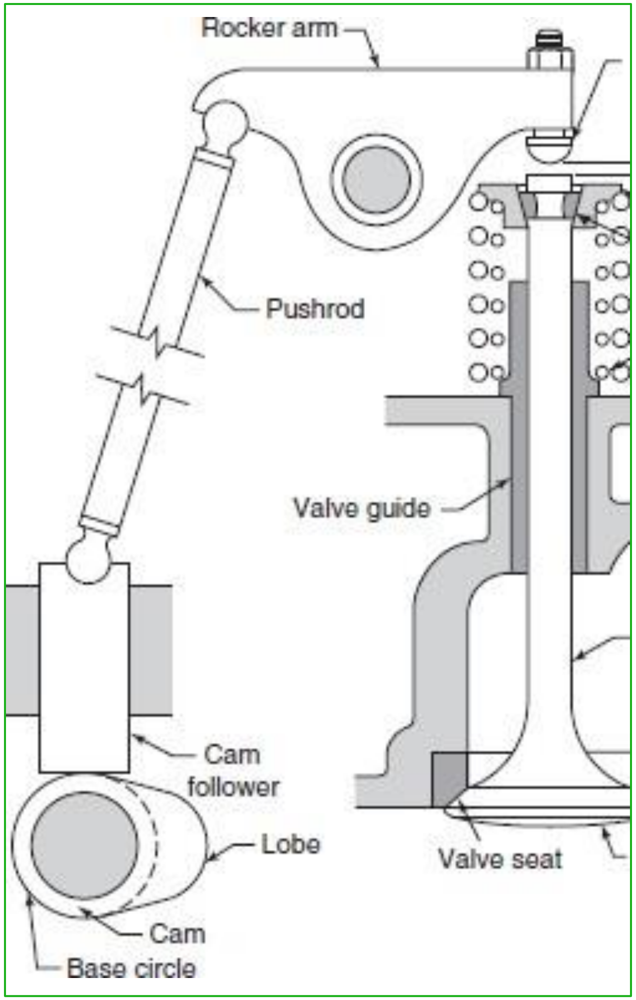
✓ **Engine valves require a finite time to actuate.**

✓ **Ideally, valves would open and close instantaneously, but this is not possible when using a camshaft. Cam profiles must allow for smooth interaction with the cam follower, and this results in fast but finite valve actuation.**

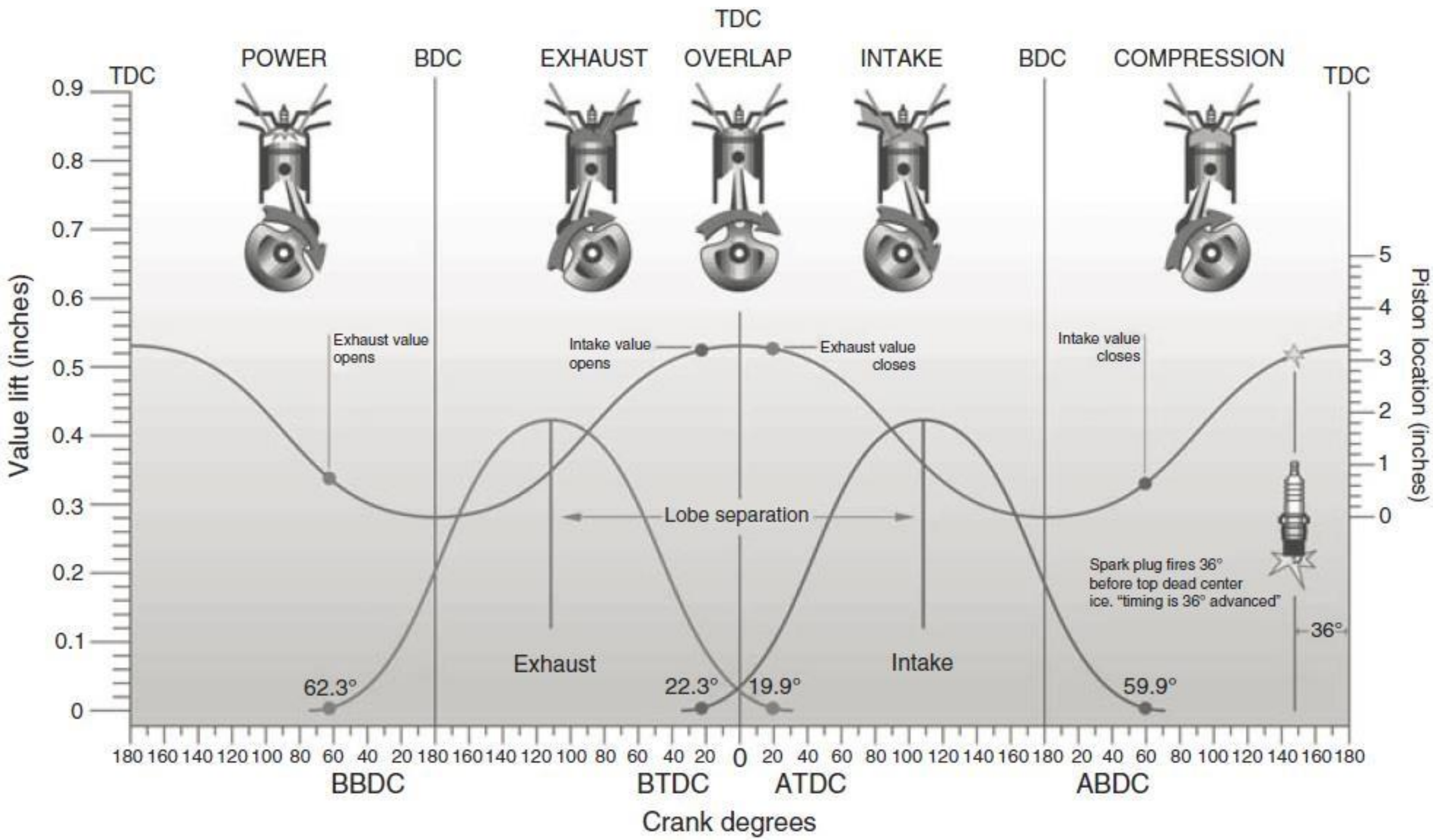
✓ **To assure that the intake valve is fully open at the start of the induction stroke, it must start to open before TDC.**

✓ **Likewise, the exhaust valve must remain fully open until the end of the exhaust stroke, with final closure occurring after TDC.**

✓ **The resulting valve overlap period causes a deviation from the ideal cycle.**



❑ Valve Timing in IC Engine



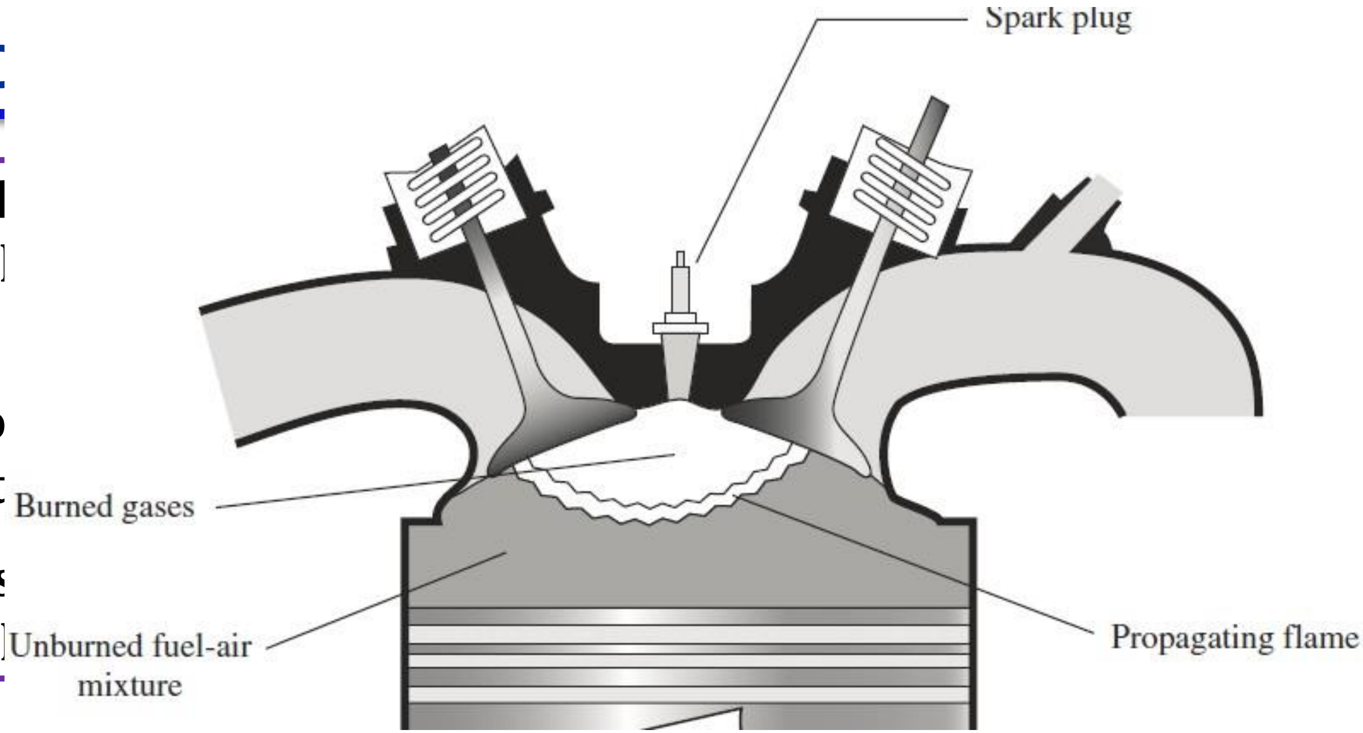
❖Week 07

Combustion

❑ C

- ✓Defined
chemical
fuel and
- ✓Rapid o
and heat
- ✓Combus
chemical

$_2 + cH_2O$



❑ Flame

- ✓A flame is a combustion reaction which can propagate subsonically through space
- ✓Motion of the flame relative to the unburned gas is the important feature.
- ✓The reaction zone is usually called the flame front

Combustion

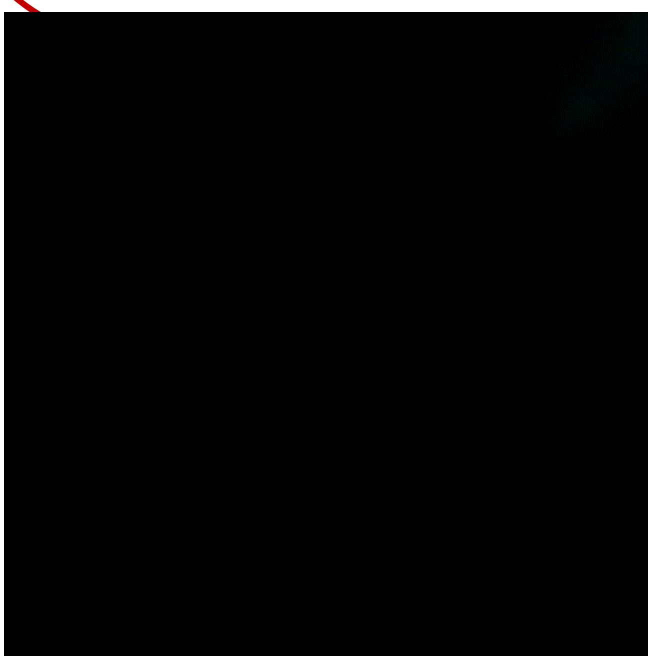
Flame

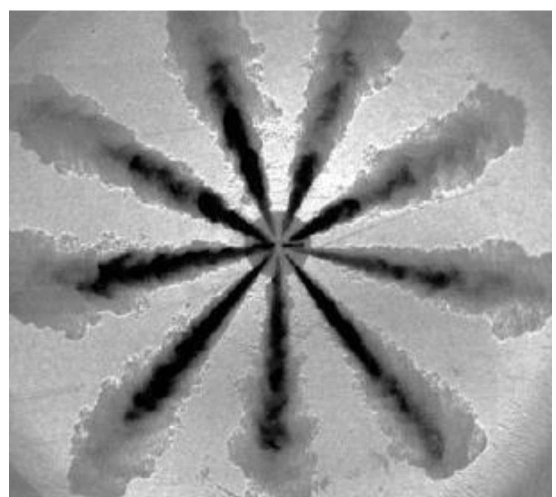
Premixed

- ✓Fuel and oxidizer are mixed at the molecular level prior to the occurrence of any significant chemical reaction.

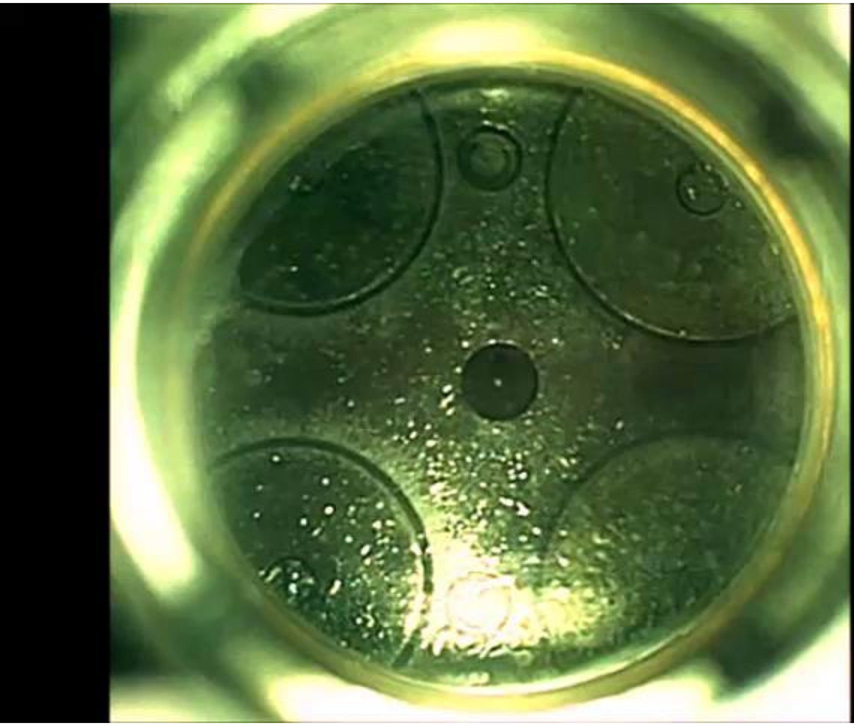
Non-premixed/Diffusion

- ✓Reactants mix together in the same region where reaction takes place
- ✓Mixing must be accomplished by a diffusion

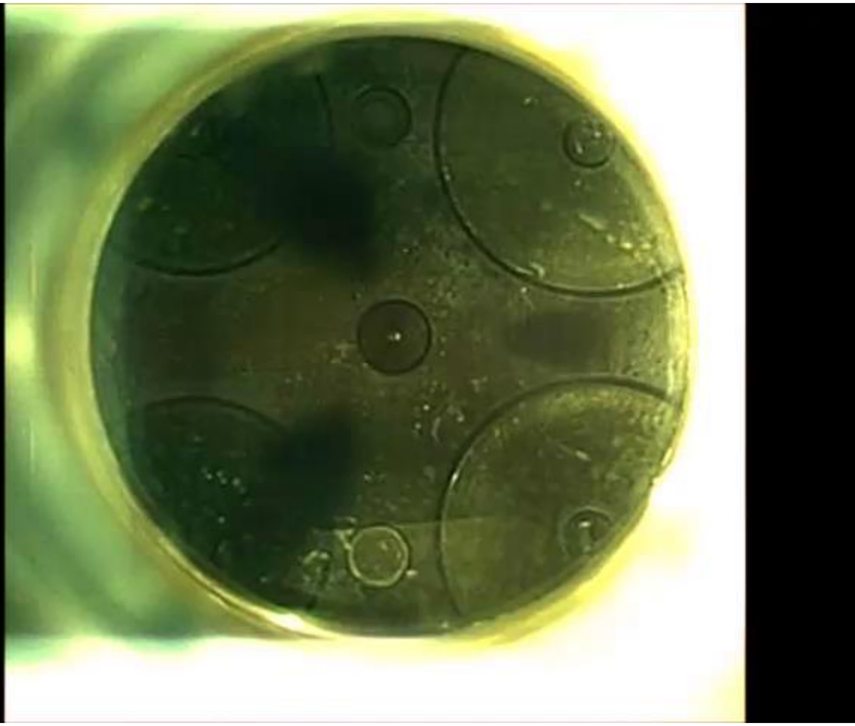




Deterioration of performance with θ_2=5°ATDC



θ_{inj}=5°BTDC single
m_{inj}=0.6mg/cycle



θ_{inj}=5°BTDC/5°ATDC split
m_{inj}=0.3/0.3mg/cycle

Combustion

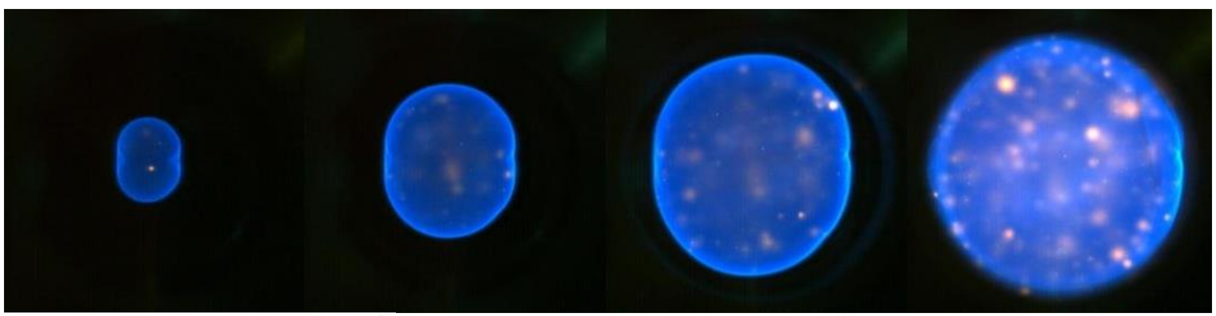
Flame

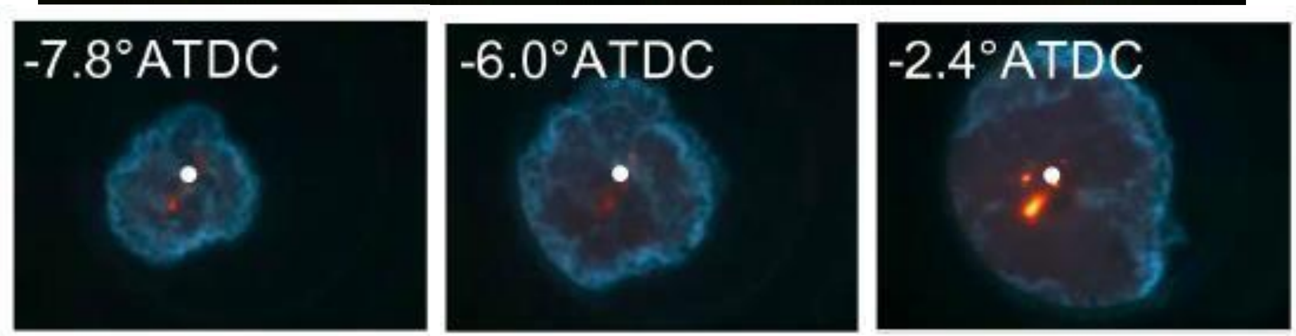
Laminar

- ✓ mixing and transport are done by molecular processes
- ✓ occur at low Reynolds number

Turbulent

- ✓ Mixing and transport are enhanced (usually by a substantial factor) by the macroscopic relative motion of eddies or lumps of fluid





Combustion in IC engines

❑ Composition of Air and Fuel

✓ O_2 = 21% (v/v)
✓ N_2 = 79% (v/v)

TABLE 3.1
Principle constitutents of dry air

Gas	ppm by volume	Molecular weight	Mole fraction	Molar ratio
O_2	209,500	31.998	0.2095	1
N_2	780,900	28.012	0.7905	3.773
Ar	9,300	39.948		
CO_2	300	44.009		
Air	1,000,000	28.962	1.0000	4.773

✓ For each (1) mole of oxygen in air there are 3.773 moles of atmospheric nitrogen.

Combustion in IC engines

Combustion Stoichiometry

- ✓ **Relations between the composition of the reactants (fuel and air) of a combustible mixture and the composition of the products.**
- ✓ **The carbon in the fuel is then converted to carbon dioxide CO_2, and the hydrogen to water H_2O.**

$$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$$

- ✓ **Consider the complete combustion of a general hydrocarbon fuel of average molecular composition C_aH_b with air. The overall complete combustion equation is**

Fuel / Air

$$\underbrace{C_aH_b}_{\text{Fuel}} + \left(a + \frac{b}{4}\right)\underbrace{(O_2 + 3.773N_2)}_{\text{Air}} = aCO_2 + \frac{b}{2}H_2O + 3.773\left(a + \frac{b}{4}\right)N_2$$

Combustion in IC engines

Combustion Stoichiometry

Fuel — Air

$$\underbrace{C_aH_b}_{\text{Fuel}} + \left(a + \frac{b}{4}\right)\underbrace{(O_2 + 3.773N_2)}_{\text{Air}} = aCO_2 + \frac{b}{2}H_2O + 3.773\left(a + \frac{b}{4}\right)N_2$$

- ✓ **Fuel composition could have been written CH_y where, *$y = b/a$***
- ✓ **The equation defines the stoichiometric (or chemically correct or theoretical) proportions of fuel and air; i.e., there is just enough oxygen for conversion of all the fuel into completely oxidized products.**

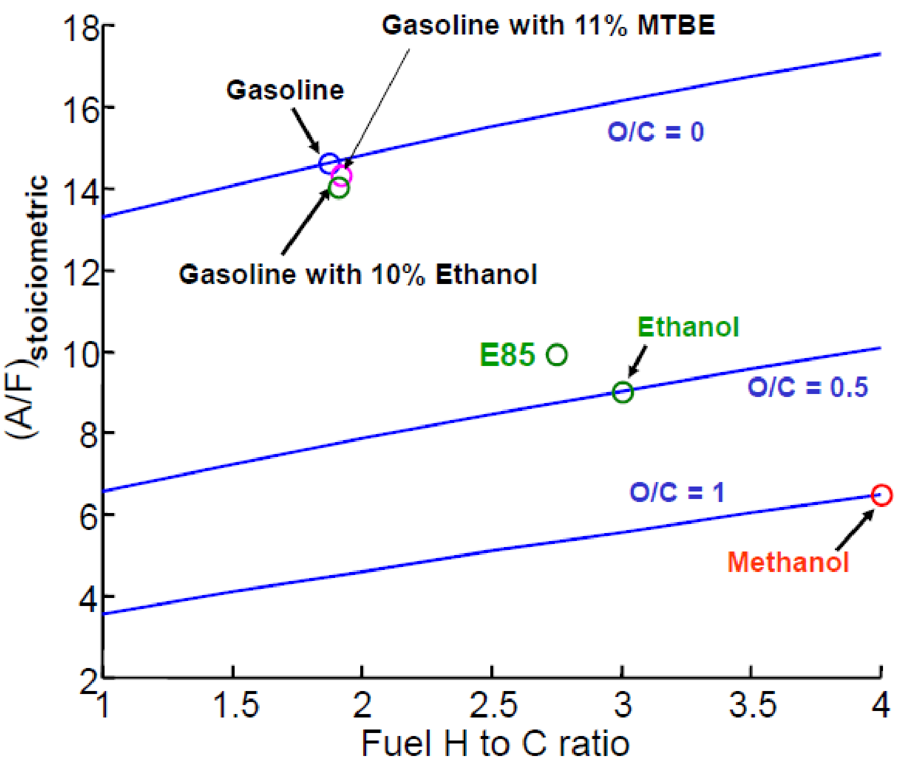
$$\left(\frac{A}{F}\right)_s = \left(\frac{F}{A}\right)_s^{-1} = \frac{(1 + y/4)(32 + 3.773 \times 28.16)}{12.011 + 1.008y}$$

$$= \frac{34.56(4 + y)}{12.011 + 1.008y}$$

Combustion in IC engines

Combustion Stoichiometry

$$\left(\frac{A}{F}\right)_s = \left(\frac{F}{A}\right)_s^{-1} = \frac{34.56(4+y)}{12.011+1.008y}$$



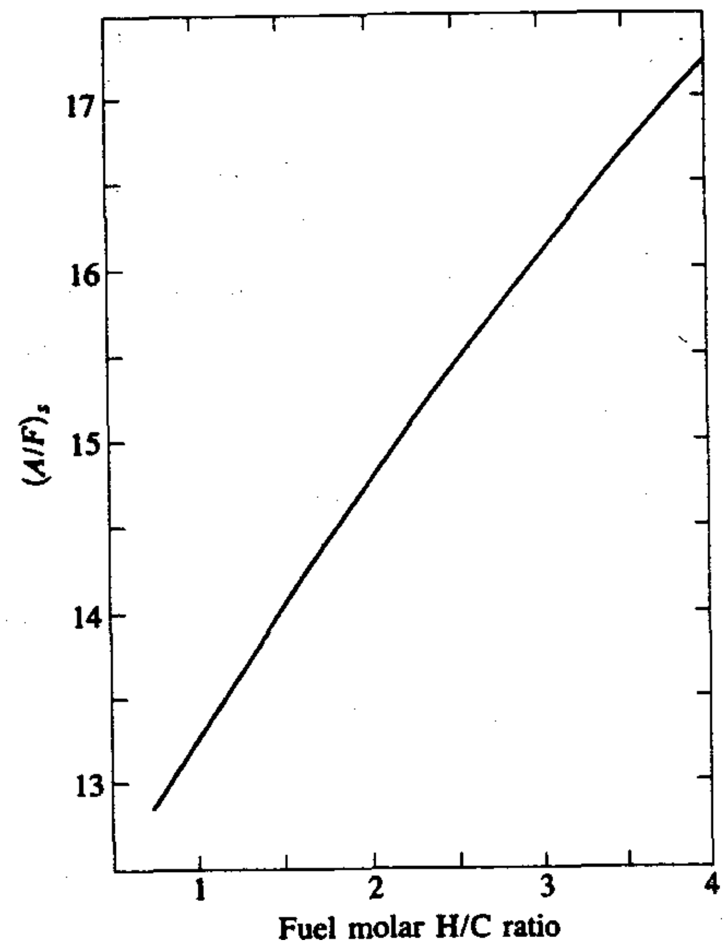


Fig.: Stoichiometric air/fuel ratio for air-hydrocarbon fuel mixtures as a function of fuel molar H/C ratio

Equivalence Ratio

- $\phi < 1$: Fuel lean mixture
  - ✓ Oxygen in exhaust

$$C_8H_{18} + 1.25 \times 12.5(O_2 + 3.773N_2) = 8CO_2 + 9H_2O + 3.13O_2 + 58.95N_2$$

- $\phi > 1$: Fuel rich mixture

✓ products are a mixture of CO_2 and H_2O with carbon monoxide CO and hydrogen H_2 (as well as N_2).

- $\phi = 1$: Stoichiometric mixture

✓ Maximum energy released from the fuel

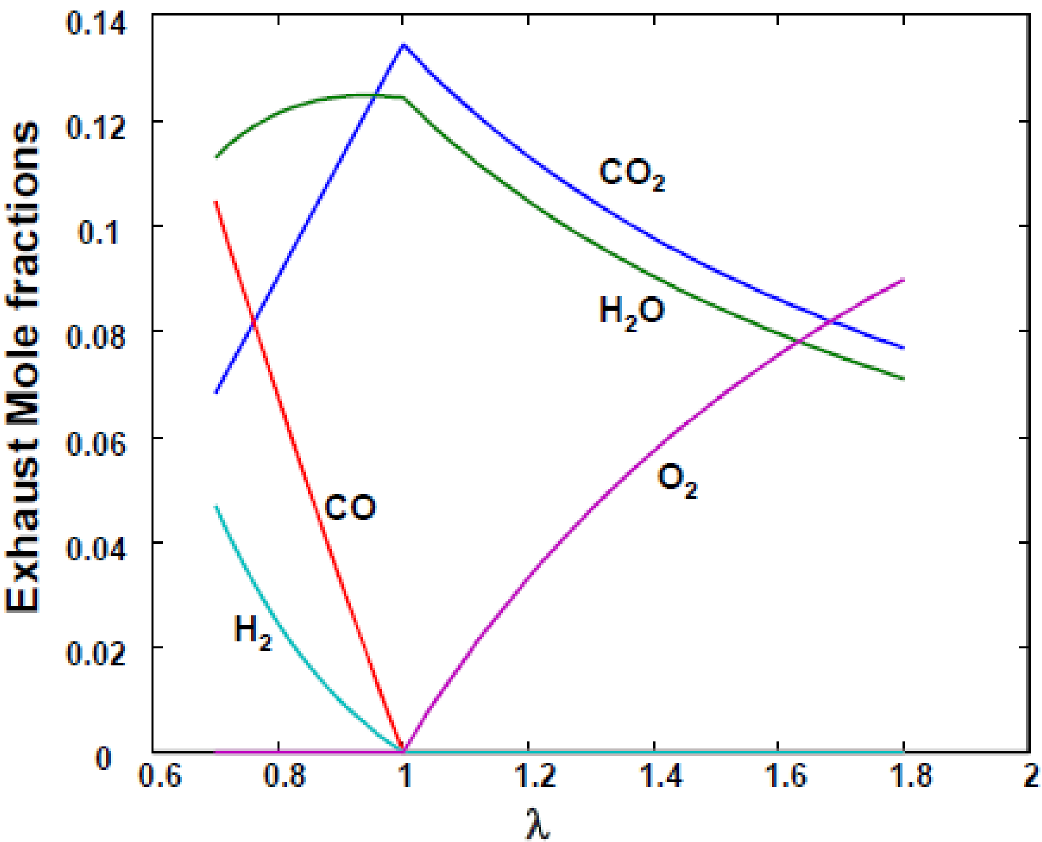
Exhaust composition (fuel $CH_{1.85}$)

Fuel-lean combustion

- major products: CO_2, H_2O, O_2, N_2
- minor products: HC, CO, H_2, NO

Fuel-rich combustion

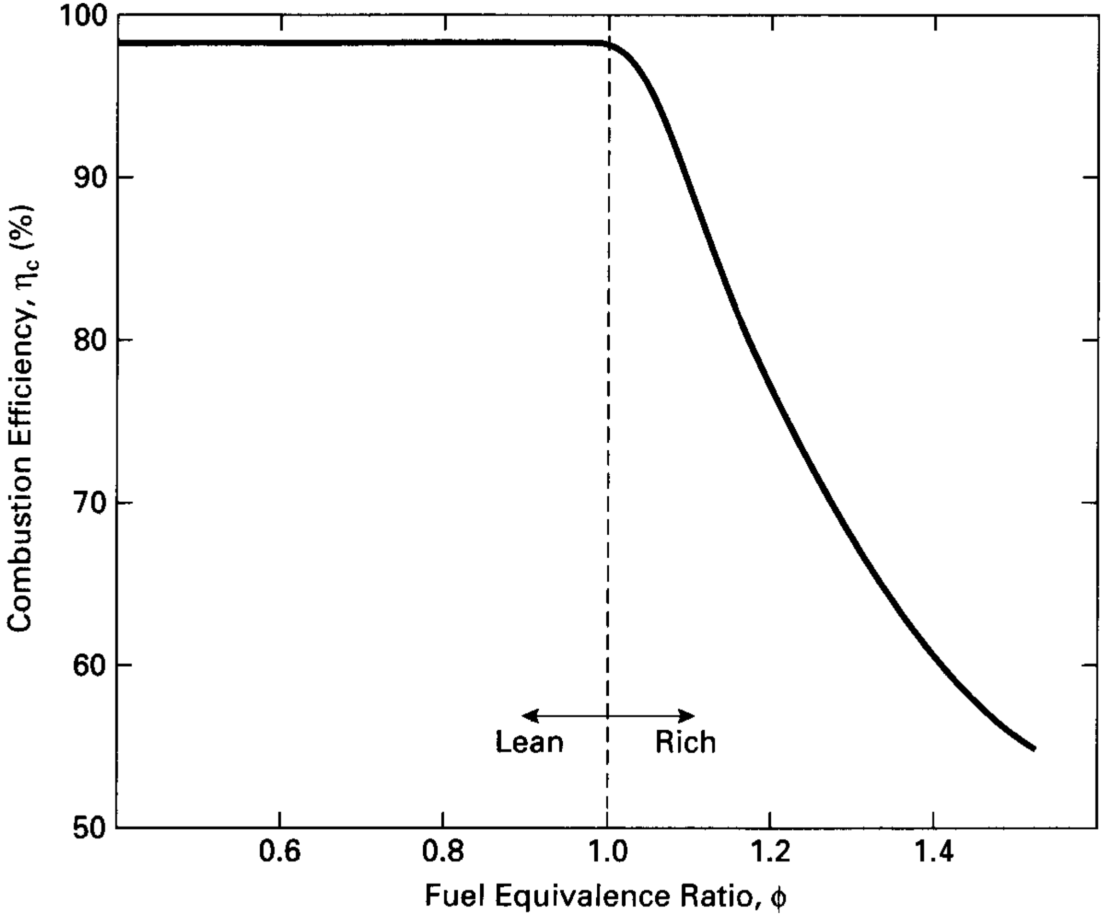
- major products: CO_2, H_2O, CO, H_2, N_2
- minor products: HC, O_2, NO



✓ **Components other than CO_2, H_2O and N_2 are found in the exhaust products**

✓ **One major reason for this is the extremely short time available for each engine cycle, which often means that less than complete mixing of the air and fuel is obtained.**

Combustion efficiency as a function of ϕ



Reference:
✓ **Engineering Fundamentals of the Internal Combustion Engine,**
-by Willard W. Pulkrabek

Fig.4-1 : Combustion efficiency as a function of fuel equivalence ratio. Efficiency for engines operating lean is generally on the order of 98%. When an engine operates fuel rich, there is not enough oxygen to react with all the fuel, and combustion efficiency decreases. CI engines operate lean and typically have high combustion efficiency.

Example 3.1. A hydrocarbon fuel of composition 84.1 percent by mass *C* and 15.9 percent by mass *H* has a molecular weight of 114.15. Determine the number of moles of air required for stoichiometric combustion and the number of moles of products produced per mole of fuel. Calculate $(A/F)_s$ and $(F/A)_s$

- Assume a fuel composition $C_a H_b$. The molecular weight relation gives,

  - $114.15 = 12.011a + 1.008b$

- The gravimetric analysis of the fuel gives,

$$\frac{b}{a} = \frac{15.9/1.008}{84.1/12.011} = 2.25$$

  - $a = 8$
  - $b = 18$

Fuel | Products

$$C_8H_{18} + 12.5(O_2 + 3.773N_2) = 8CO_2 + 9H_2O + 47.16N_2$$

Air

- $C_8 H_{16} + (12.5/0.2095)(0.2095 * O_2 + 0.2095*3.773 N_2) = 8CO_2 + 9H_2O + 47.16N_2$

Example 3.1. **A hydrocarbon fuel of composition 84.1 percent by mass *C* and 15.9 percent by mass *H* has a molecular weight of 114.15. Determine the number of moles of air required for stoichiometric combustion and the number of moles of products produced per mole of fuel. Calculate $(A/F)_s$ and $(F/A)_s$**

Air

- $C_8H_{18} + 12.5/0.2095\,(0.2095\,O_2 + 0.2095*3.773\,N_2) = 8CO_2 + 9H_2O + 47.16N_2$

$$C_8H_{18} + 12.5(O_2 + 3.773N_2) = 8CO_2 + 9H_2O + 47.16N_2$$

- **In moles:**

$$1 \quad + 12.5(1 + 3.773) \quad = 8 + 9 + 47.16$$

$$1 \quad + \quad 59.66 \quad = 64.16$$

- **Thus for stoichiometric combustion, 1 mole of fuel requires 59.66 moles of air and produces 64.16 moles of products.**

- **Relative mass:**

Molecular weight of Air

$$114.15 + 59.66 \times 28.96 \quad = 8 \times 44.01 + 9 \times 18.02 + 47.16 \times 28.16$$

$$114.5 \quad + 1727.8 \quad = 1842.3$$

Example 3.1. A hydrocarbon fuel of composition 84.1 percent by mass *C* and 15.9 percent by mass *H* has a molecular weight of 114.15. Determine the number of moles of air required for stoichiometric combustion and the number of moles of products produced per mole of fuel. Calculate $(A/F)_s$ and $(F/A)_s$

- **Relative mass:**

Molecular weight of Air

$$114.15 + \underbrace{59.66 \times 28.96} = 8 \times 44.01 + 9 \times 18.02 + 47.16 \times 28.16$$

$$114.5 \quad + 1727.8 \quad = 1842.3$$

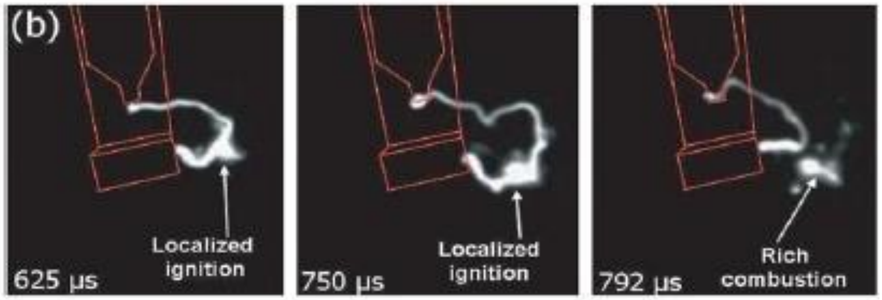
- **Per unit mass of fuel:**

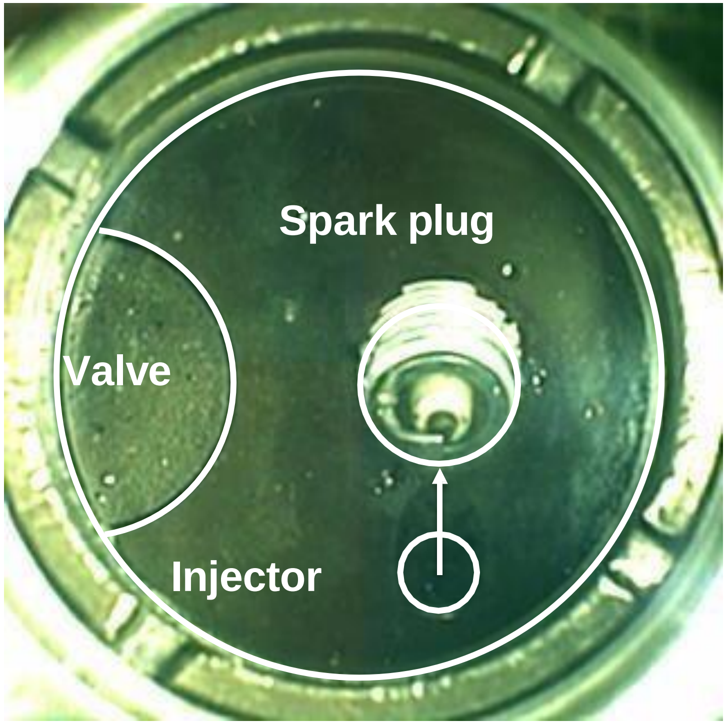
$$1 \quad + \quad 15.14 \quad = \quad 16.14$$

- **Thus stoichiometric $(A/F)_s$ is 15.14 and $(F/A)_s$ is 0.0661.**

Combustion in SI engines

❑ Stages of Combustion





Combustion in SI engines

❑ Stages of Combustion

- Combustion process of SI engines can be divided into three broad regions:

Ignition and flame development

✓ Combustion is initiated towards the end of the compression stroke at the spark plug by an electric discharge

Flame propagation

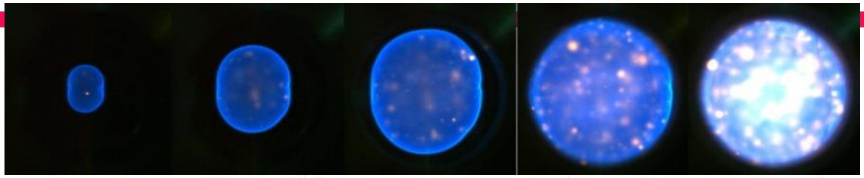
✓ A turbulent flame develops, propagates through this essentially premixed fuel, air, burned gas mixture

Flame Termination

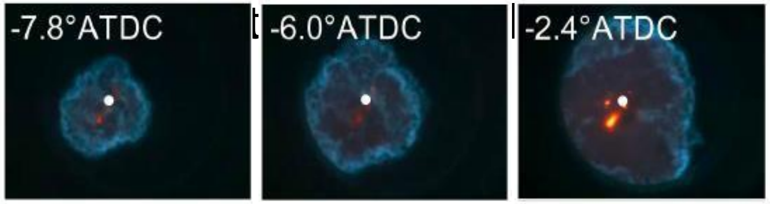
✓ until it reaches the combustion chamber walls, and then extinguishes

Combustion in SI engines

❑ Stages of Combustion



➢ **Combustion process of SI engines can be di**

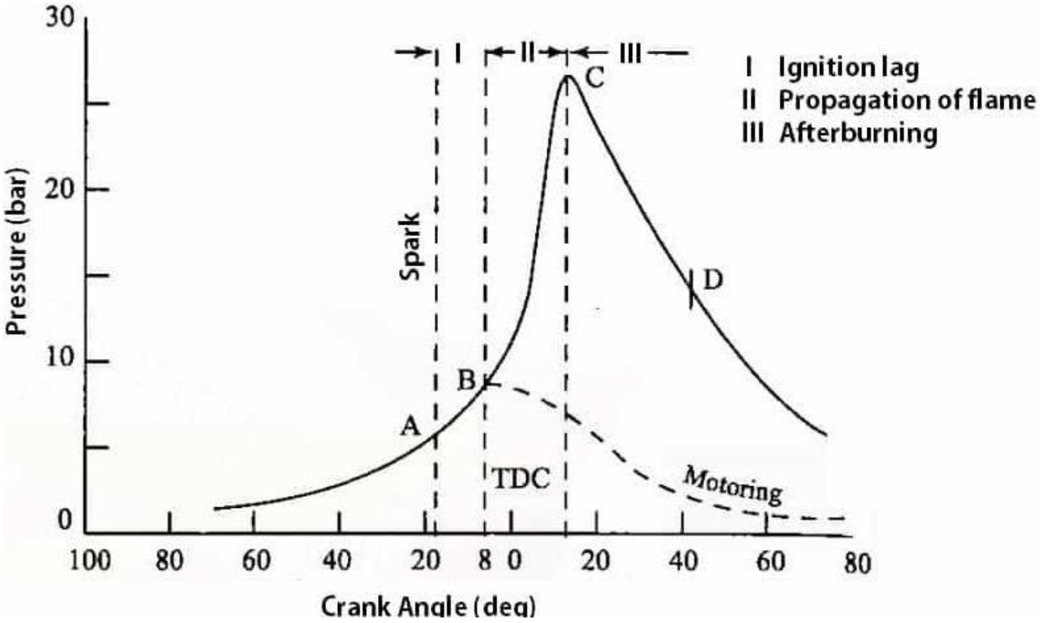


Ignition and flame development

✓ **Combustion is initiated towards the end of the compression stroke at the spark plug by an electric discharge**

Flame propagation

✓ **A turbulent flame develops, propagates through this essentially premixed fuel, air, burned gas mixture**

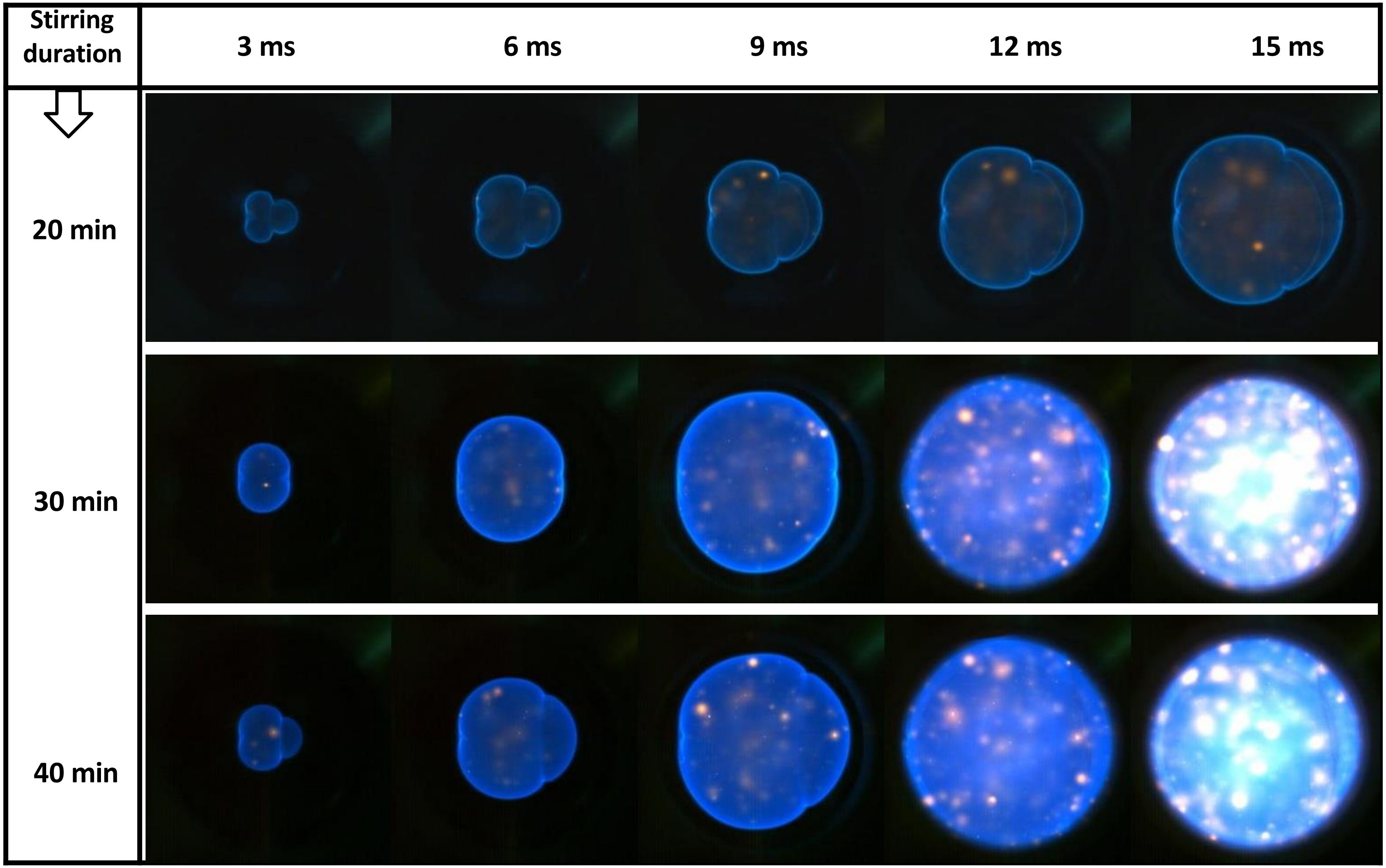


Flame Termination

✓ **until it reaches the combustion chamber walls, and then extinguishes**

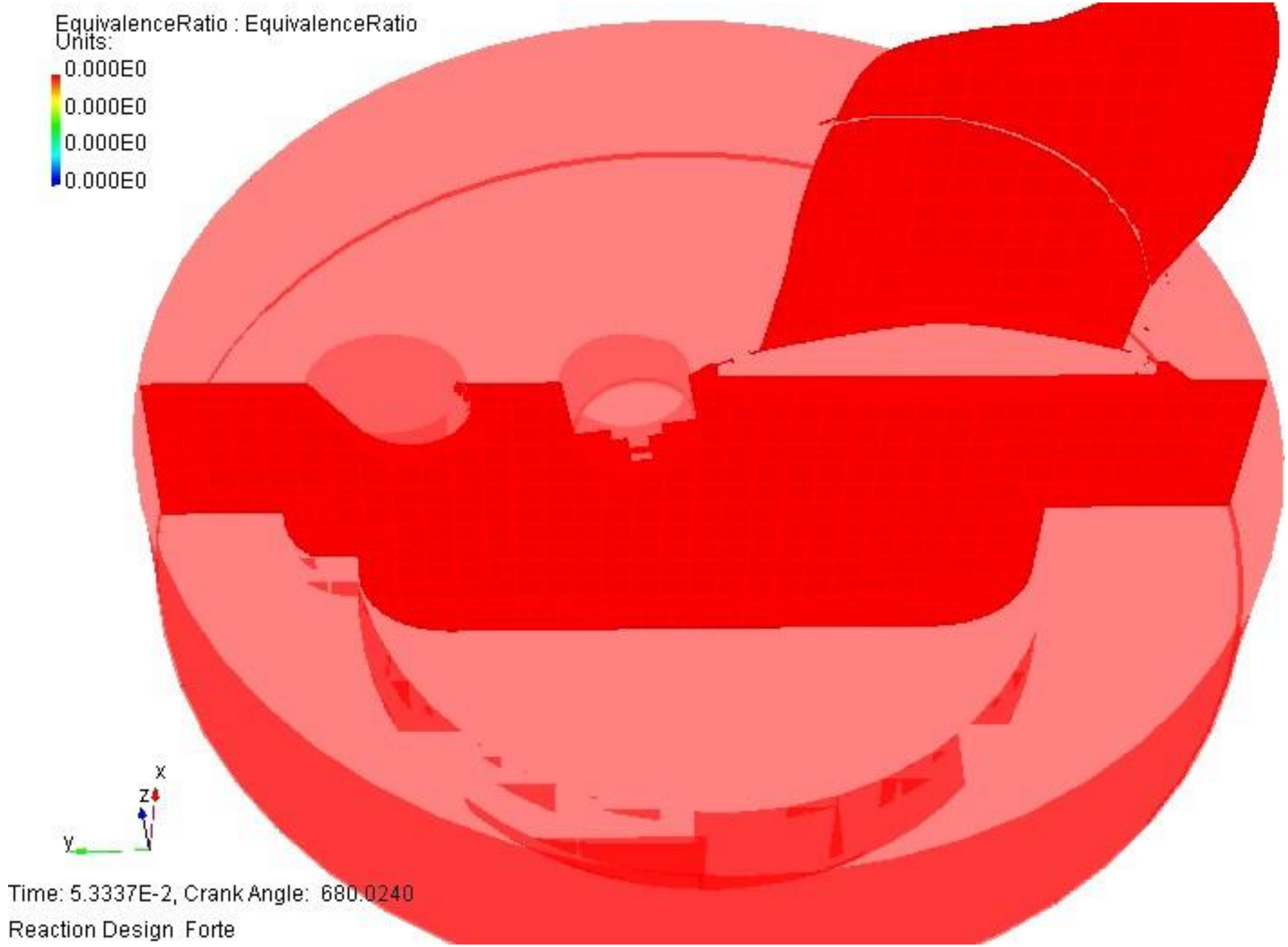
Combustion in SI engines

❑ Stages of Combustion



Modeling Hydrogen Combustion, λ=4.0

SOI = 35ºBTDC; Equivalence ratio & Flame front (Iso-contour; G=0)



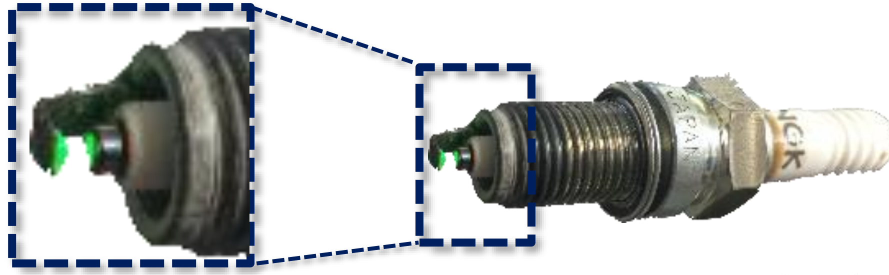
❖Week 08

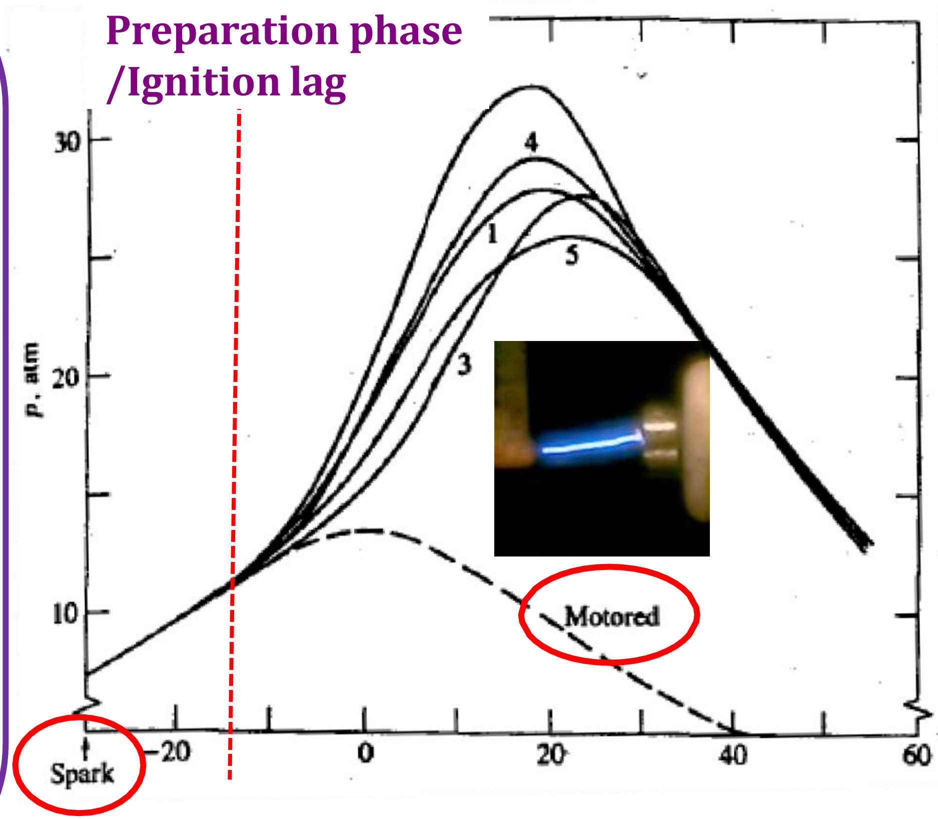
Combustion in SI engines

❑ Stages of Combustion

Ignition and flame development

- ✓ **The discharge of a spark plug delivers 30 to 50 mJ of energy, most of which, however, is lost by heat transfer**
- ✓ **Combustion starts very slowly because of the high heat losses to the relatively cold spark plug and gas mixture**
- ✓ **It is desirable to have a rich air-fuel mixture around the electrodes of the spark plug at the time of ignition**





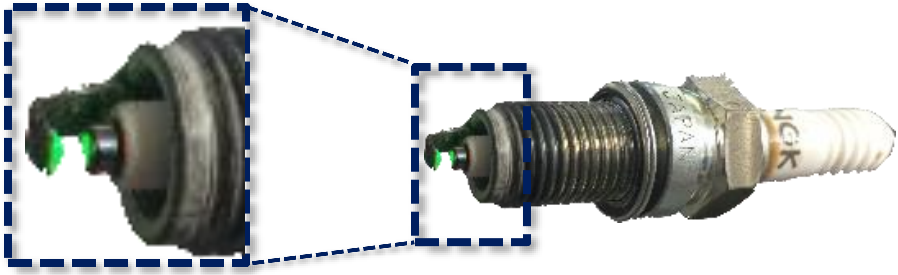
Reference:
✓ **Internal Combustion Engine Fundamentals**
-by JB Heywood

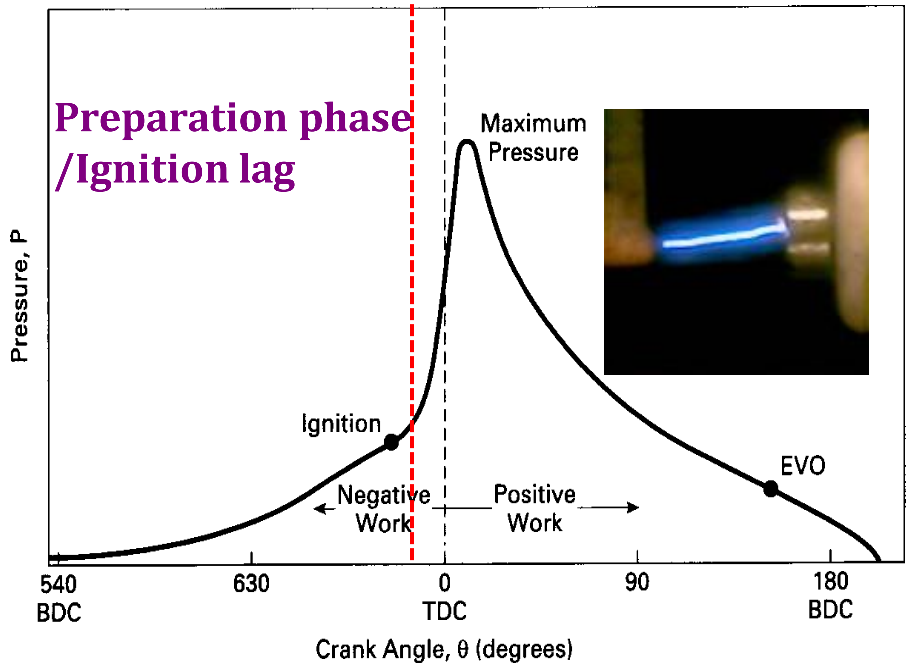
Combustion in SI engines

❑ Stages of Combustion

Ignition and flame development

- ✓ Ignition occurs and the combustion process starts, but very little pressure rise is noticeable and little or no useful work is produced
- ✓ Flame development is generally considered the consumption of the first 5% of the air-fuel mixture (some sources use the first 10%)





Reference:
✓ Engineering Fundamentals of the Internal Combustion Engine, -by Willard W. Pulkrabek

Combustion in SI engines

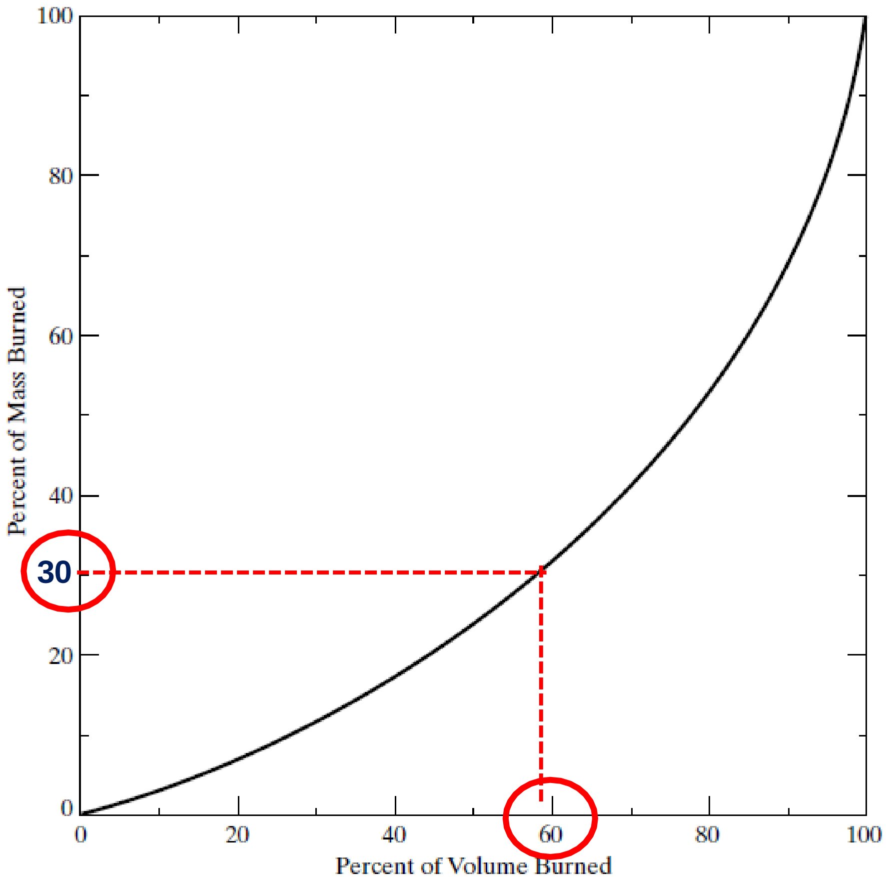
❑ Stages of Combustion

Flame Propagation

✓ A turbulent flame develops, propagates through the essentially premixed fuel, air and burned gas mixture

✓ During this time, pressure in the cylinder is greatly increased, and this provides the force to produce work in the expansion stroke

✓ Just about all useful work produced in an engine cycle is the result of the flame propagation period of the combustion process



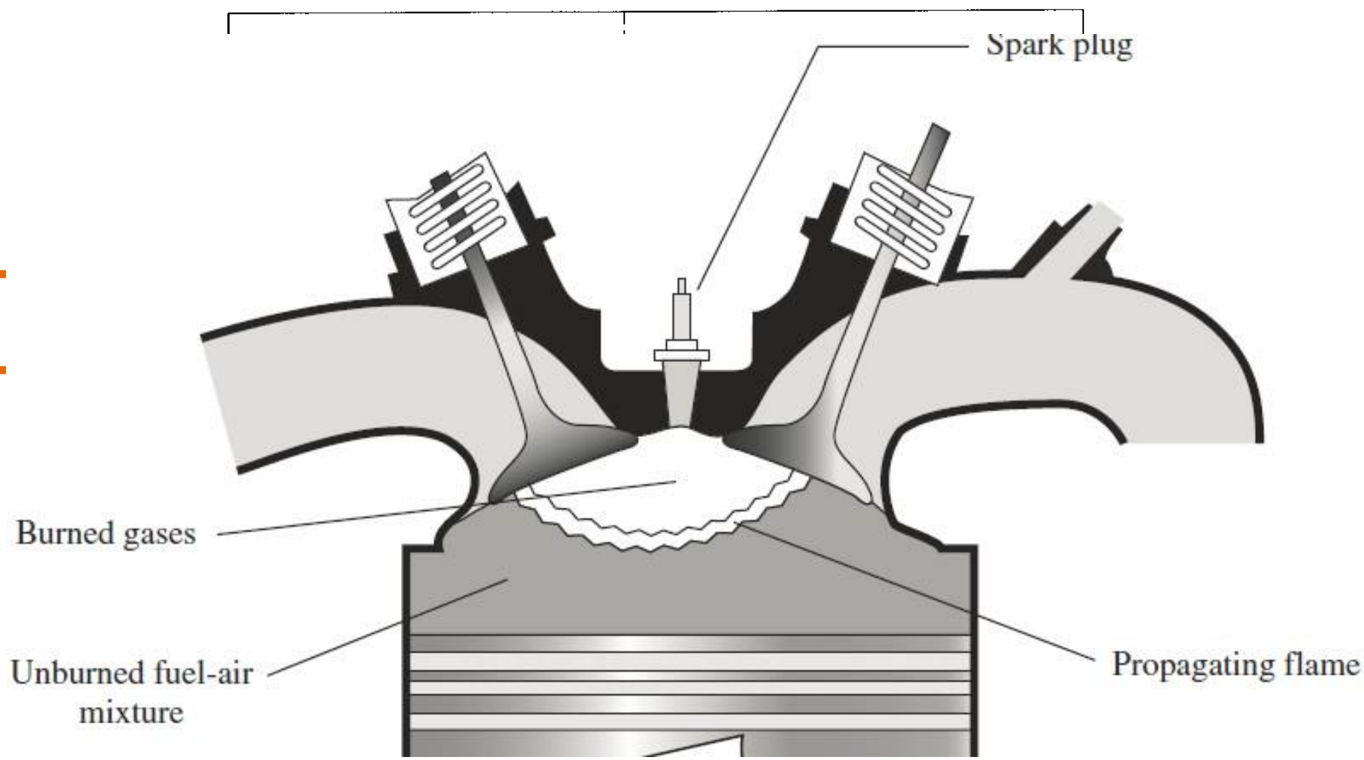
Reference:

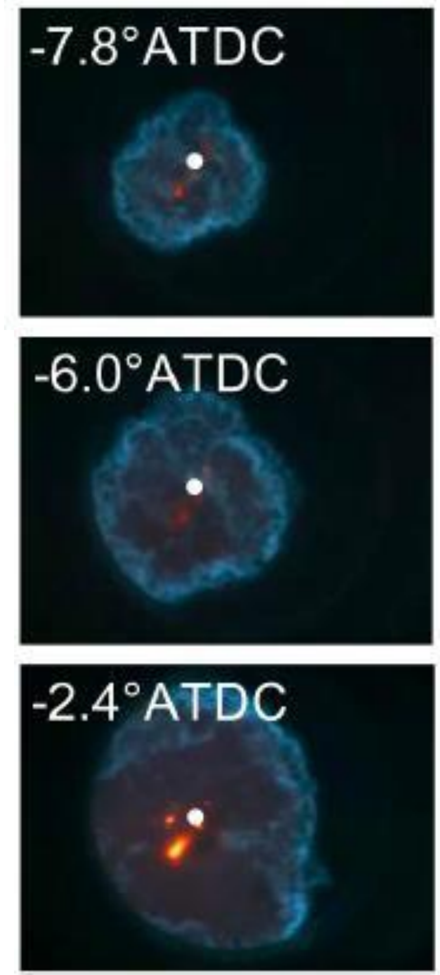
✓ Engineering Fundamentals of the Internal Combustion Engine, -by Willard W. Pulkrabek

Combustion in SI engines

❑ Abnormal Combustion

✓**Normal Combustion: initiated solely by a timed spark and flame moves steadily across the combustion chamber until the charge is fully consumed**



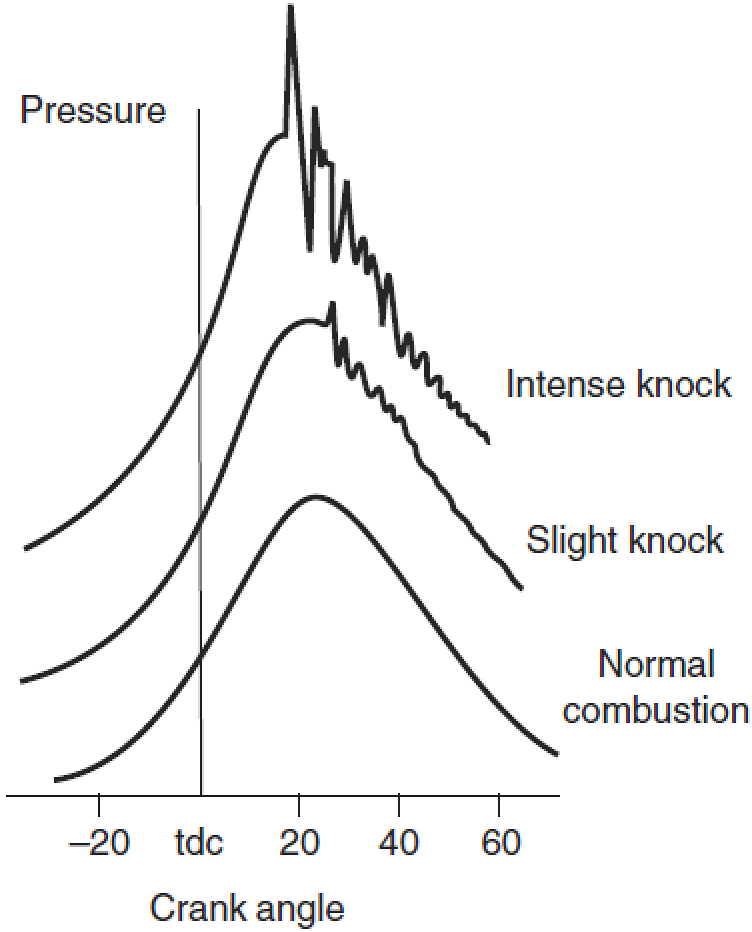


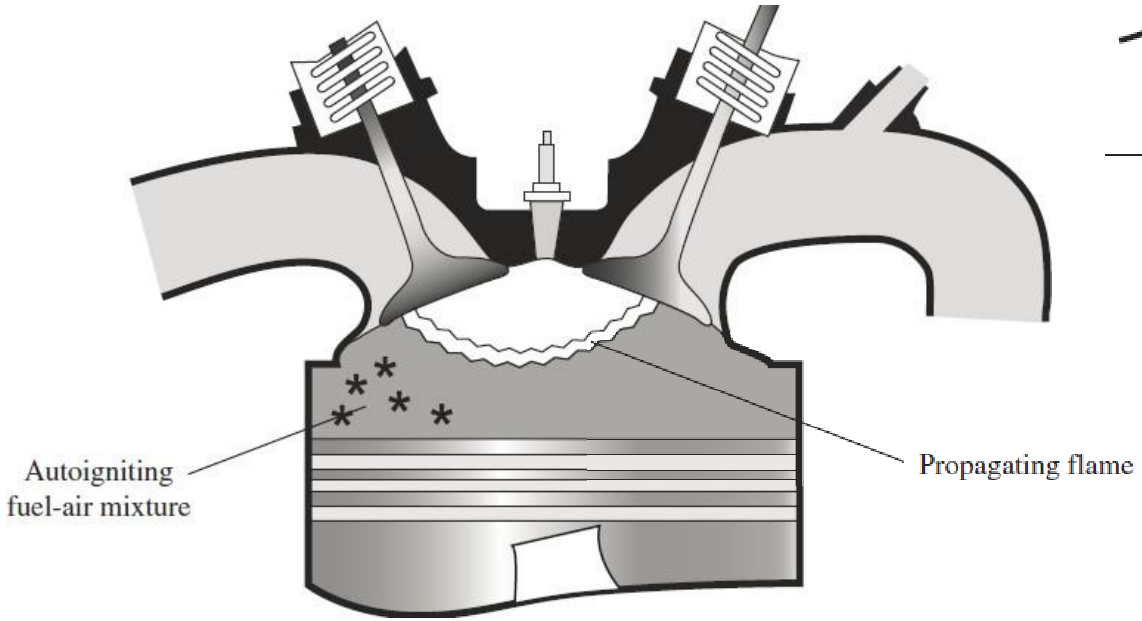
- **May occur after normal ignition (postignition)**

Abnormal Combustion in SI engines

Knock

- ✓Produces an audible high frequency pinging or "knocking" noise
- ✓Could damage the engine
- ✓Performance of spark ignition engines is limited by the onset of knock





❖Week 09

Abnormal Combustion in SI engines

❑ Knock

- ✓ Knock primarily occurs under wide-open-throttle operating conditions
- ✓ Occurrence and severity of knock depend on the knock resistance of the fuel and on the antiknock characteristics of the engine
- ✓ The ability of a fuel to resist knock is measured by its octane number

❑ Knocking Theories:

- ➢ Two theories have been advanced to explain the origin of knock:

  (i) Auto-ignition theory and

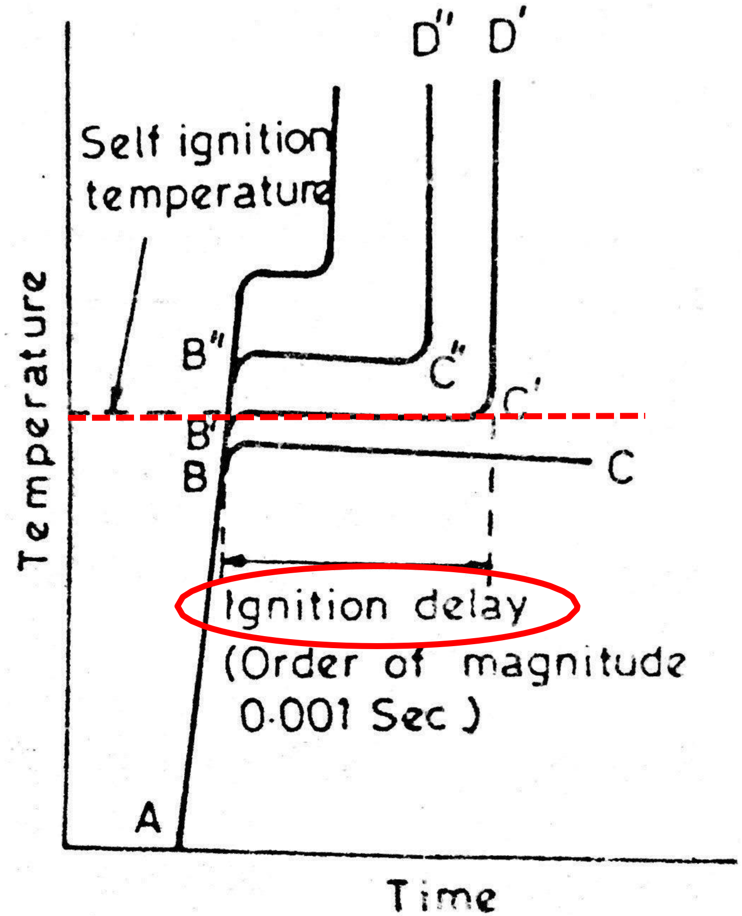
  (ii) Detonation theory

Knocking in SI engines

❑ Auto-ignition theory

➢ Ignition delay:

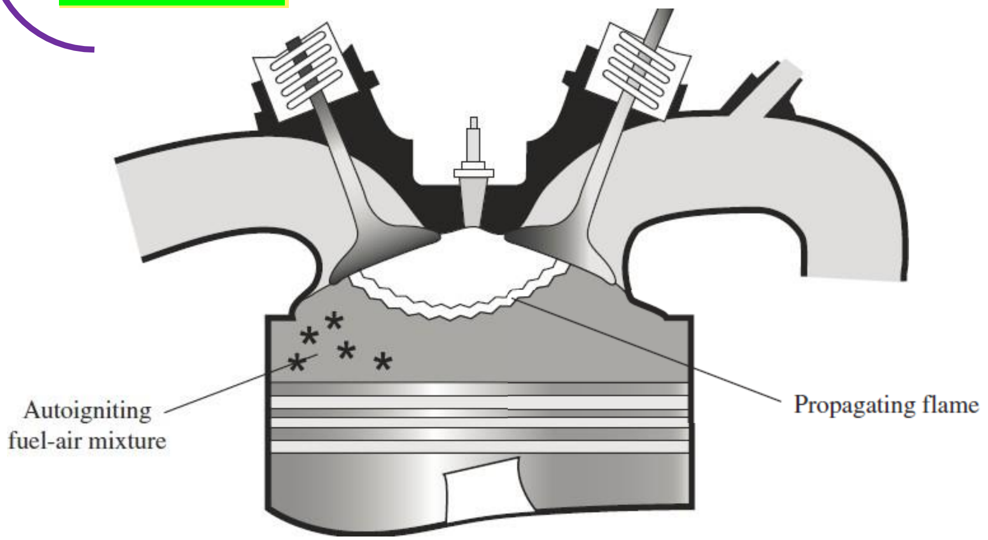
- ✓ Auto-ignition does not occur immediately when self-ignition temperature is reached
- ✓ There is a delay before the reaction becomes explosive
- ✓ During the delay period **pre-flame reactions occur**, which prepare the mixture for giving rise to a flame



Knocking in SI engines

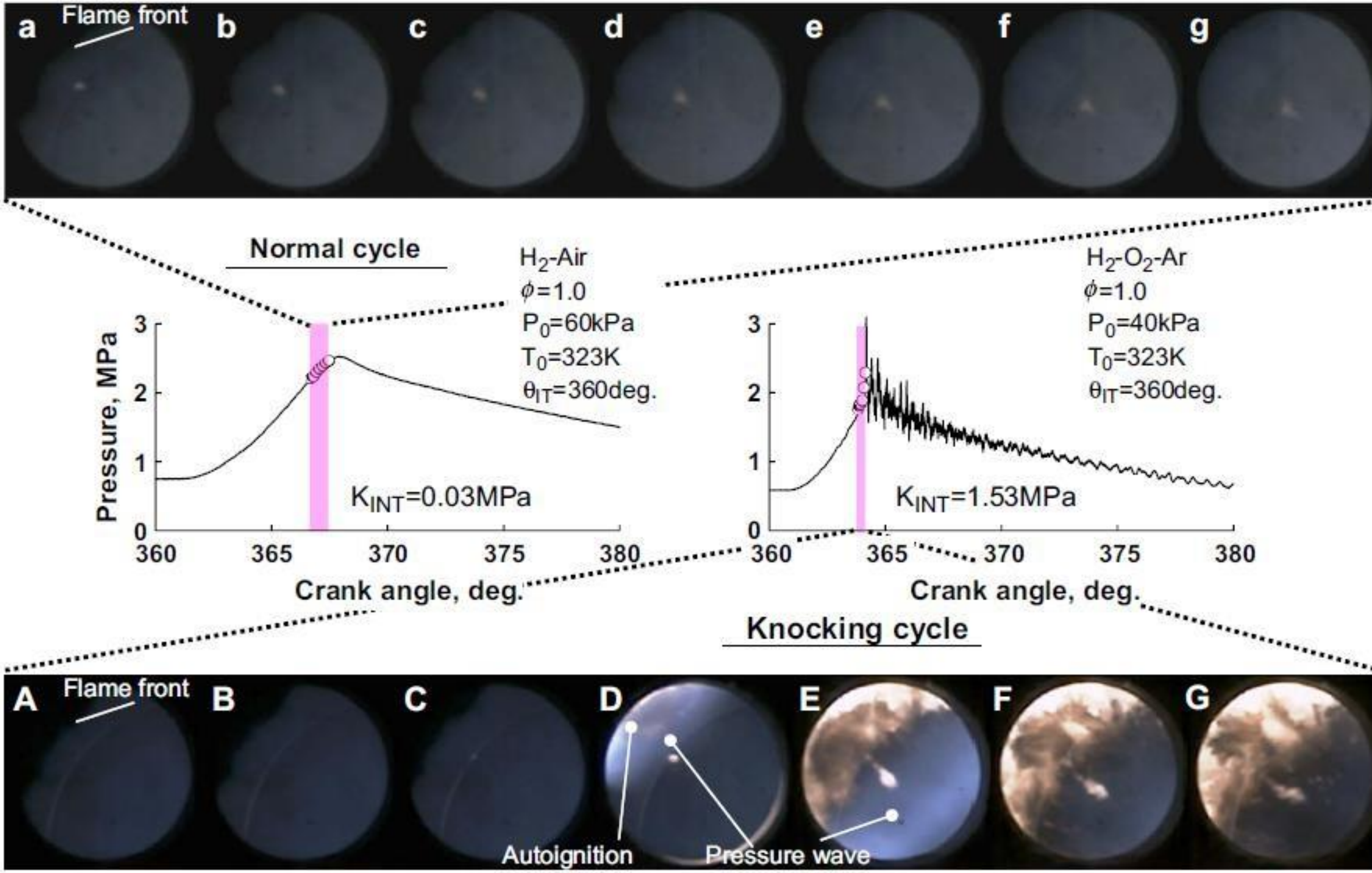
❑ Auto-ignition theory

- ✓ When end-gas is compressed to sufficiently high pressures and temperatures, the fuel oxidation process starts with the pre-flame chemistry and ends with rapid energy release (can occur spontaneously in parts or all of the end-gas region)
- ✓ A shock wave propagates from the outer edge of this high-pressure end-gas region across the chamber at supersonic velocity, and an expansion wave propagates into the high pressure region toward the near wall



Combustion in SI engines

❑ Knock



Knocking in SI engines

❑ Detonation theory

- ✓Under knocking conditions, the advancing flame front accelerates to sonic velocity and consumes the end-gas at a rate much faster than would occur with normal flame speed
- ✓Attempt to describe what causes the rapid release of chemical energy in the end-gas
- ✓There is much less evidence to support the detonation theory than the auto-ignition theory

❑ Controlling knock

- ✓End gas should have low temperature, low density
- ✓Long ignition delay
- ✓Non-reactive composition

Knocking in SI engines

Factors affecting knock

Temperature factors:

- Raising the compression ratio;
- Supercharging : will increase both the temperature and pressure
- Raising the inlet air temperature,
- Raising the coolant temperature: delay period decreases
- Raising the temperatures of the cylinder and combustion chamber walls
- Advancing the spark timing

Density factors:

- Opening the throttle (increasing the load)
- Raising compression ratio;
- Supercharging: will increase both the temperature and pressure
- Raising the inlet pressure: delay period decreases
- Advancing the spark timing

❖Week 09

Knocking in SI engines

❑ Factors affecting knock

➢ **Time factors:**

➢ **Increasing the time exposure of the unburned mixture to auto-igniting conditions by any of the following factors will increase the possibility of knock:**

✓ **Increasing the distance the flame has to travel in order to traverse the combustion chamber : compact combustion chamber & centrally located spark plug**

✓ **Decreasing the turbulence of the mixture thus decreasing the speed of the flame : design of intake, comb. chamber**

✓ **Decreasing the speed of the engine**

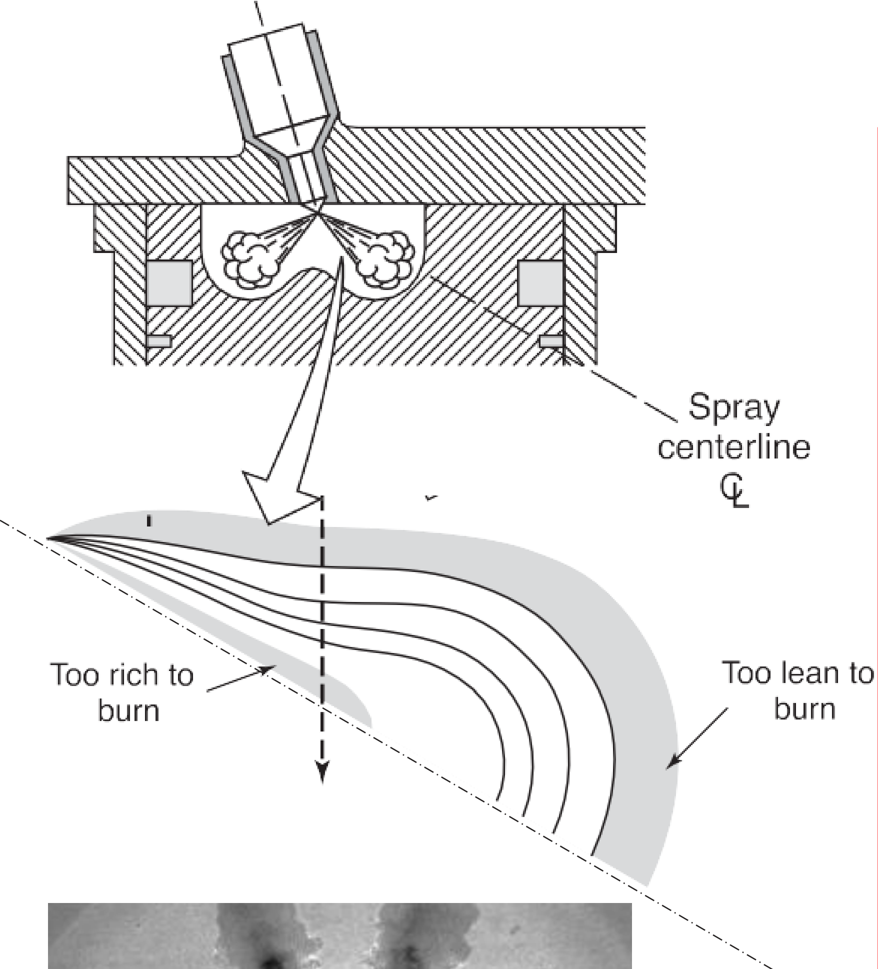
Knocking in SI engines

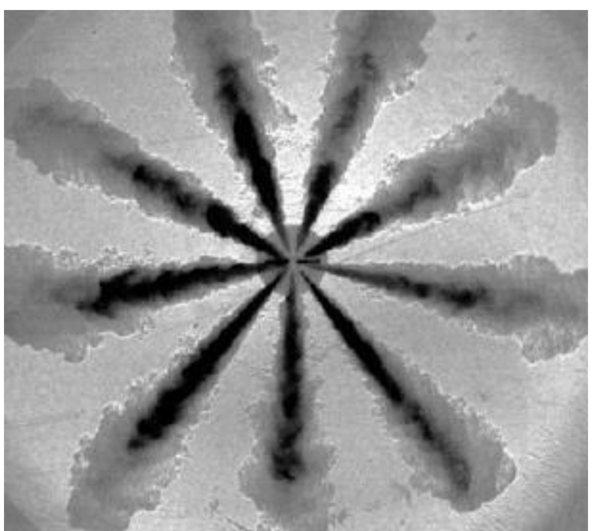
Factors affecting knock

- **Composition:**

- Properties of the fuel and fuel-air ratio are primary means of controlling knock, once compression ratio and engine dimensions are selected. The probability of knock is decreased by:

  - ✓ Increasing the octane rating of the fuel
  - ✓ Either rich or lean mixtures : longer delay and lower temp. of comp.
  - ✓ Stratifying the mixtures so that end gas is less reactive
  - ✓ Increasing the humidity of entering air : reaction time





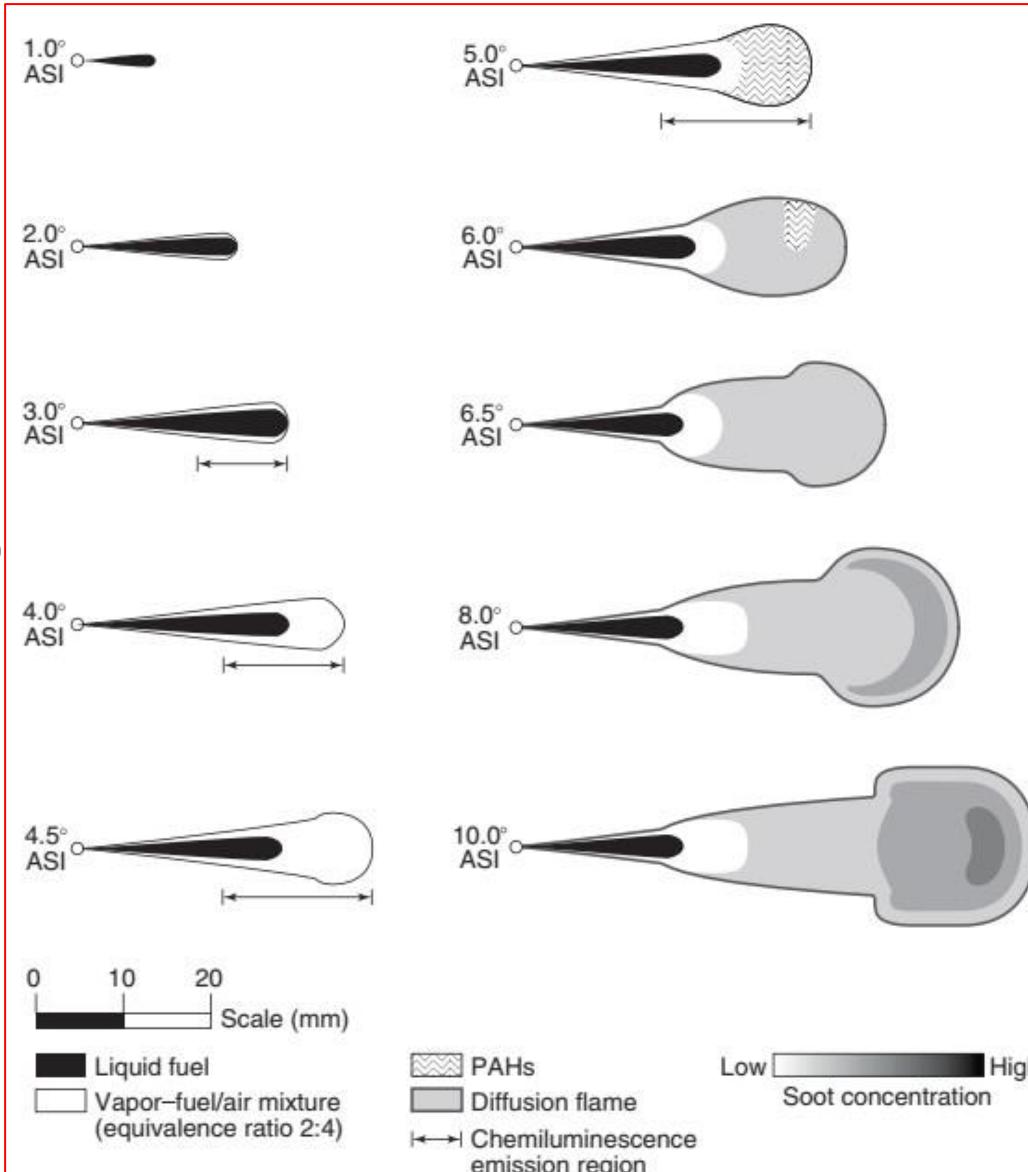


Figure 7.17 Detailed model of diesel combustion (Dec, 1997).

Combustion in CI engines

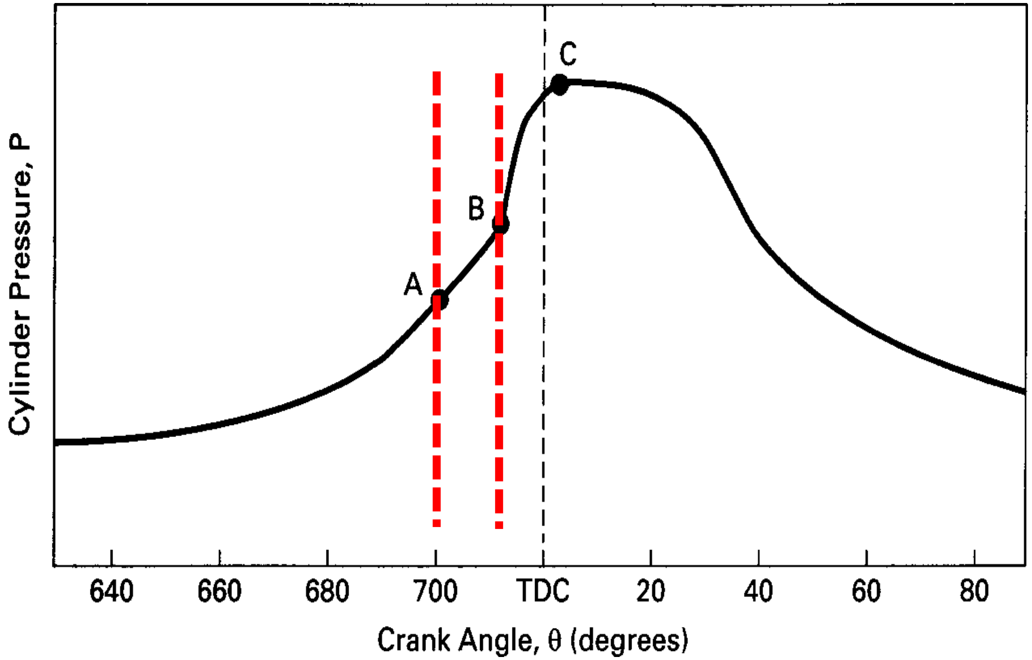
Stages of Combustion

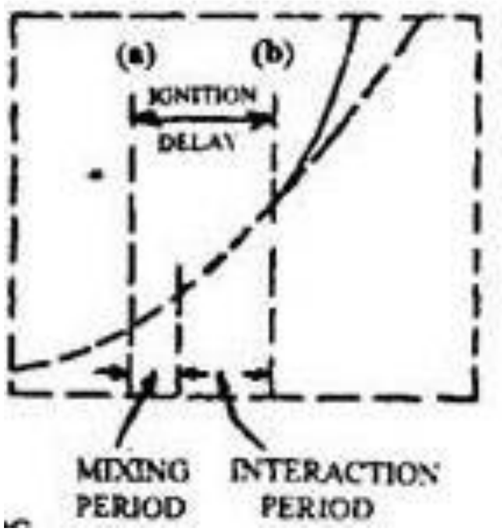
- **Ignition delay:**

Time (crank angle) interval between the start of injection (SOI) and the start of combustion

✓**Physical delay:** fuel is atomized, vaporized mixed with air and raised in temperature

✓**Chemical delay:** reactions starts slowly and then accelerates until inflammation or ignition takes place





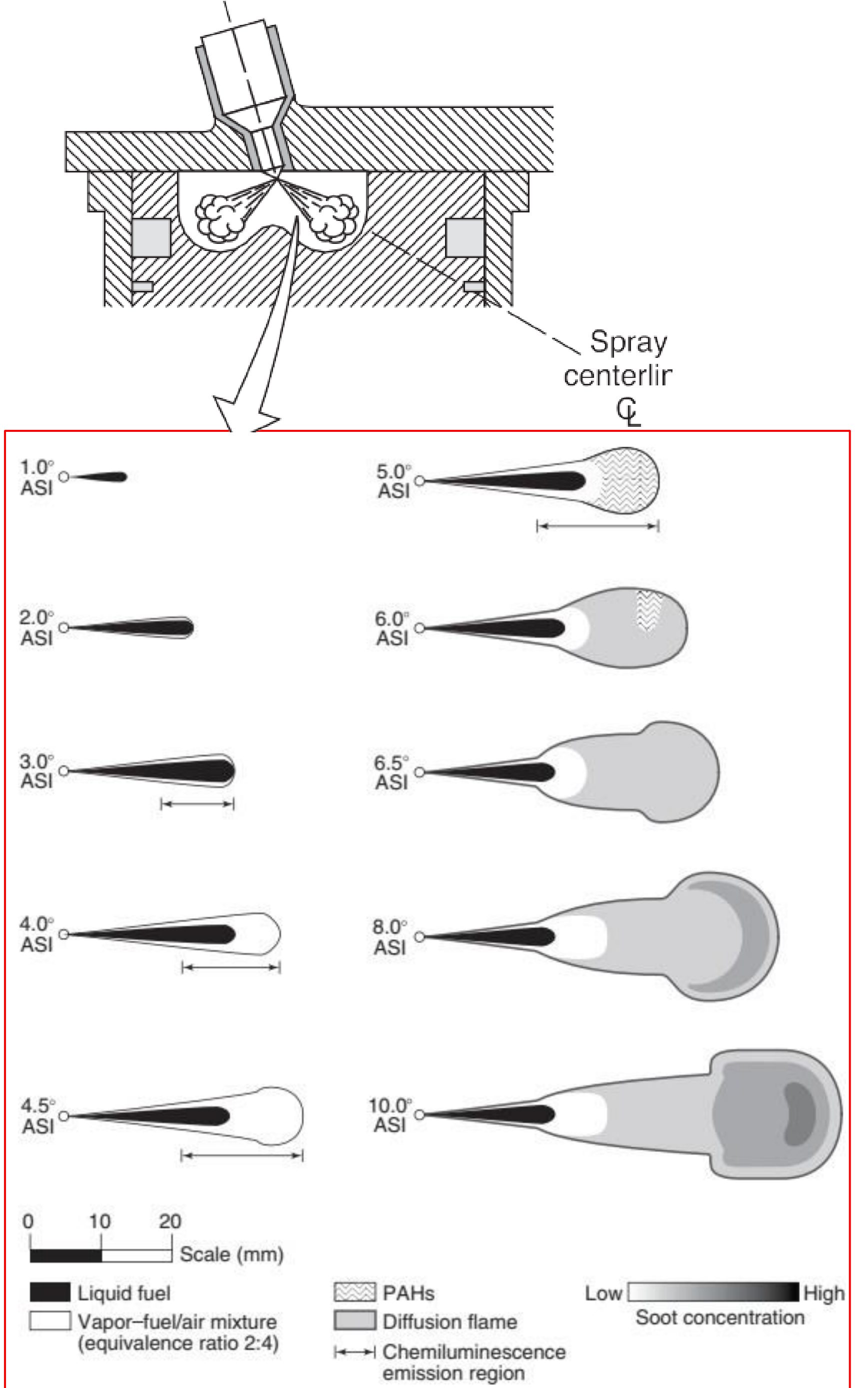
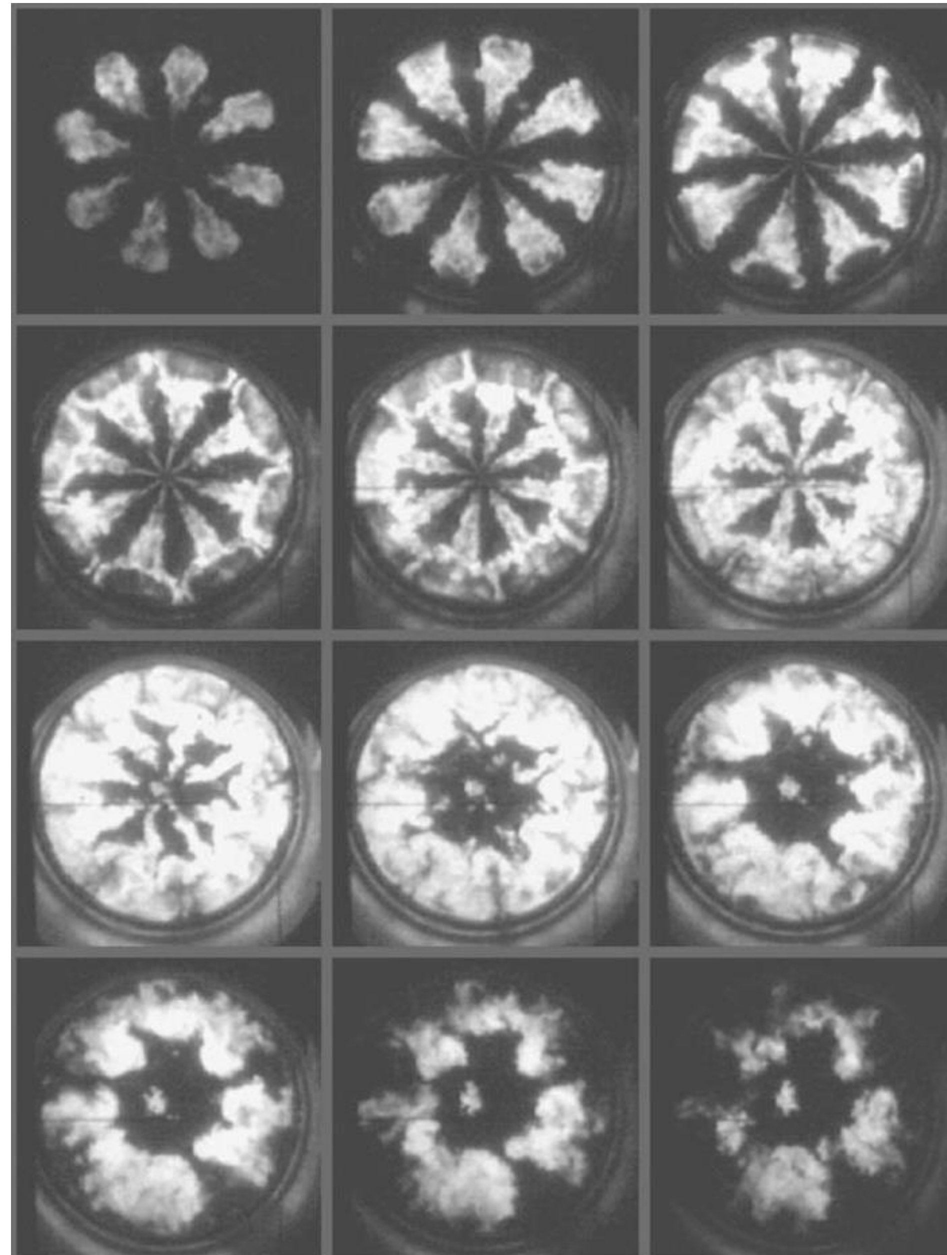
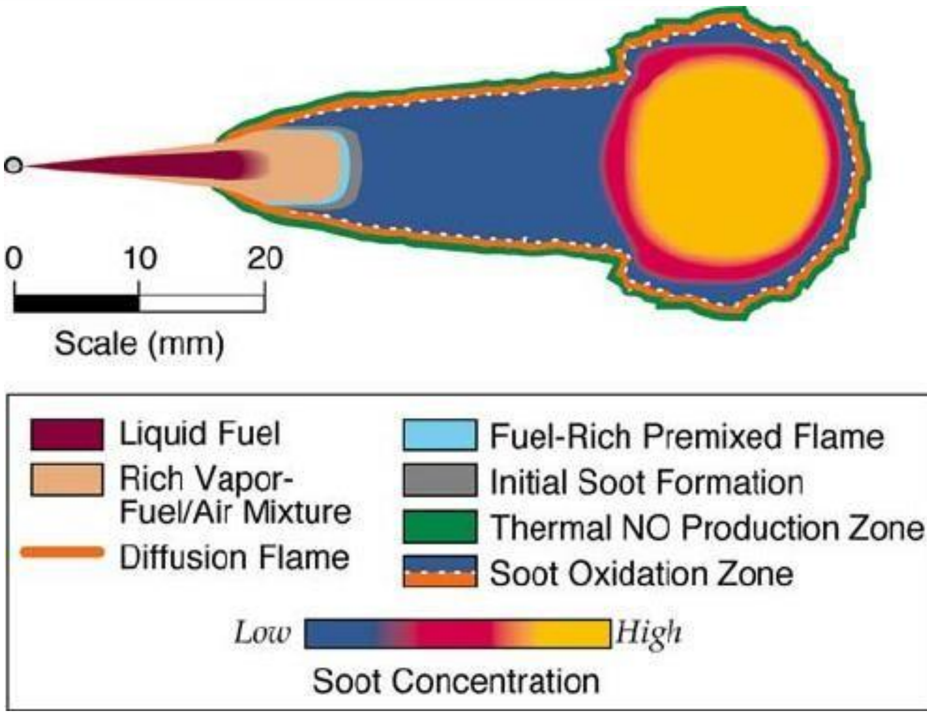


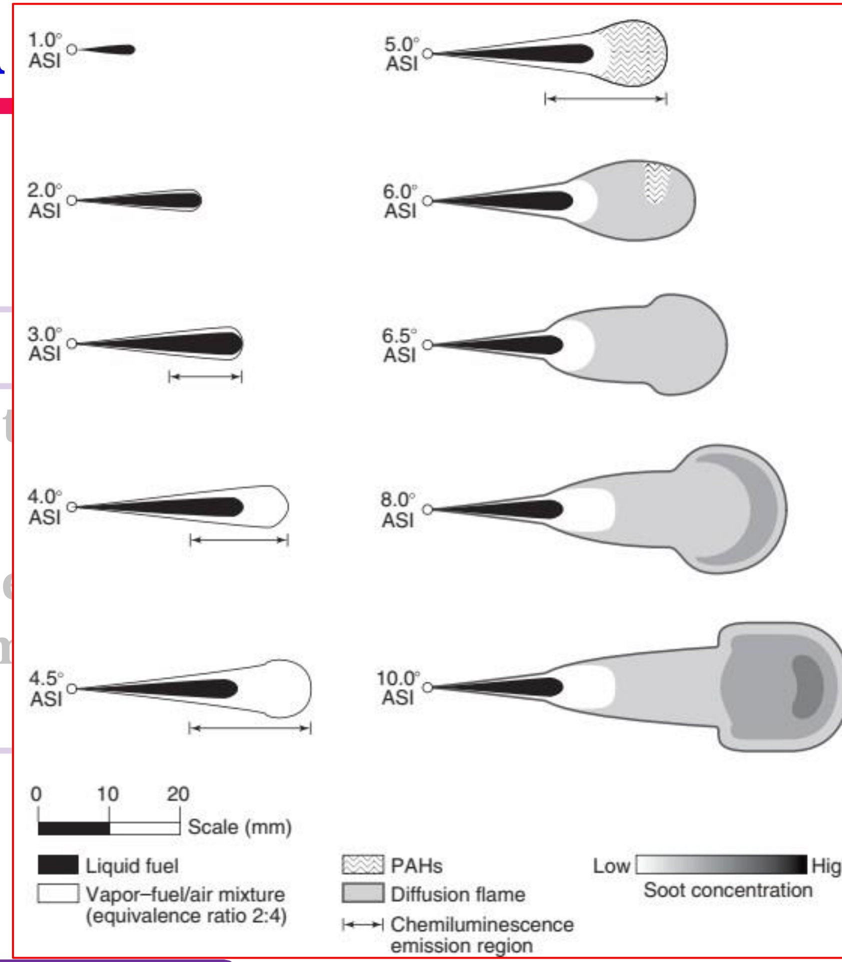
Figure 7.17 Detailed model of diesel combustion (Dec, 1997).



Combustion in

❑ Stages of Combustion



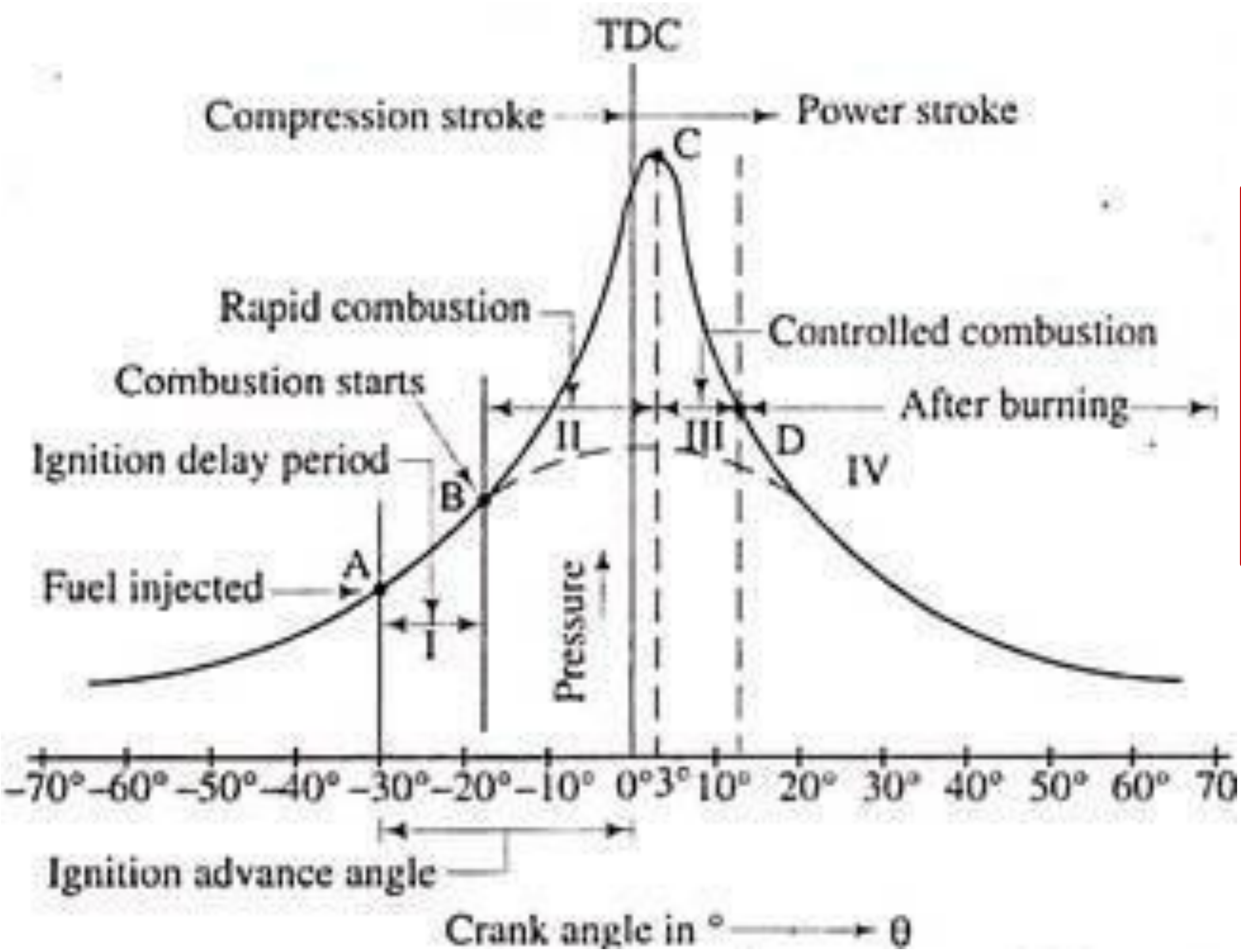


Combustion

- ✓ **Combustion starts from self-ignition simultaneously at many locations in the slightly rich zone of the fuel jet**
- ✓ **Multiple flame fronts spreading from the many self-ignition sites quickly consume all the gas mixture which is in a correct combustible air-fuel ratio**

Combustion in CI engines

Stages of Combustion



Phases of combustion

I – Ignition delay period

II – Rapid combustion

III – Controlled combustion

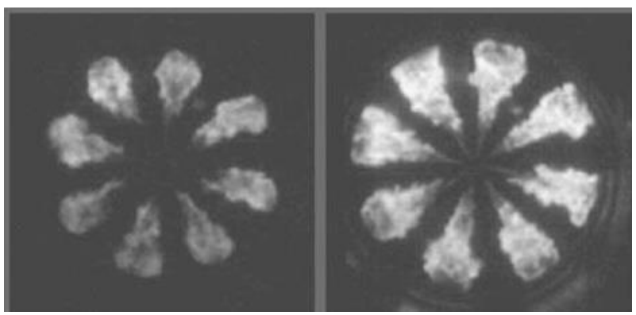
IV – After burning

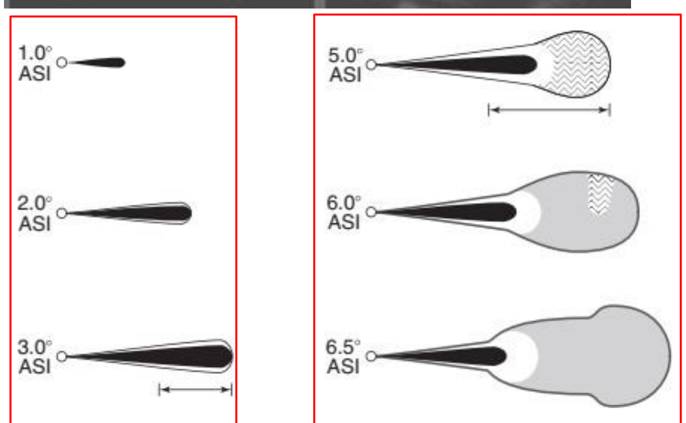
Combustion in CI engines

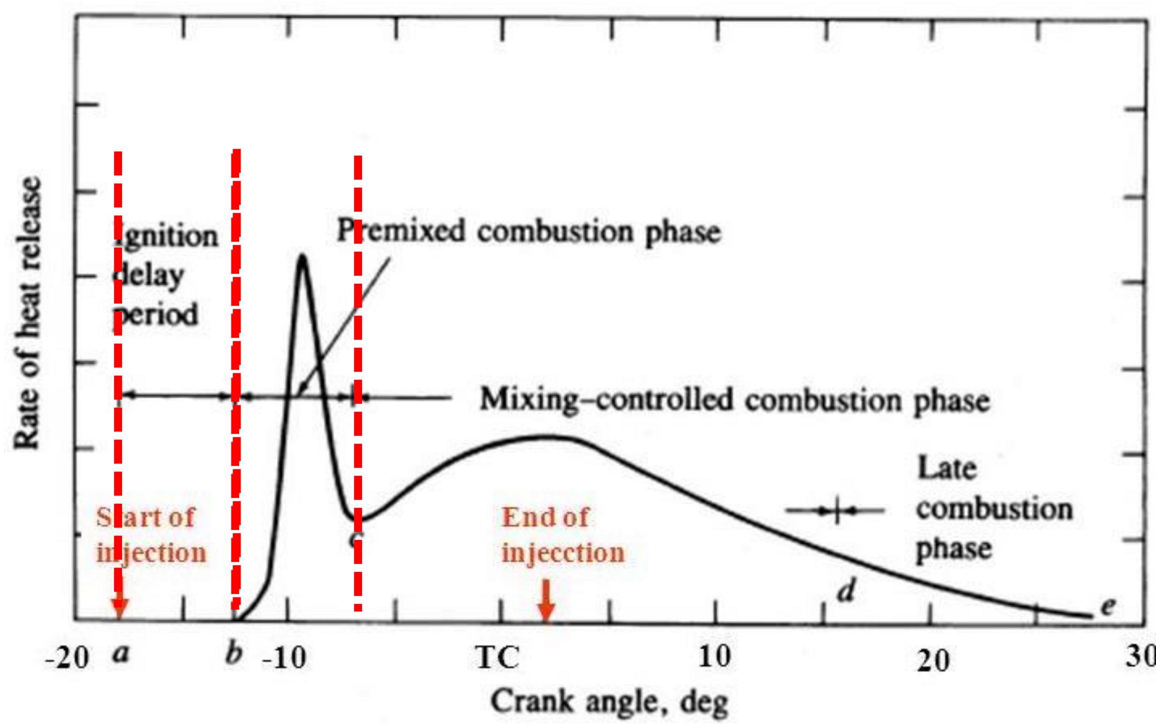
❑ Stages of Combustion

Premixed or rapid combustion phase

- ✓ **Once regions of fuel vapor--air mixture, formed around the fluid jet as it is first injected into the cylinder, are at or above the auto-ignition temperature, they will spontaneously ignite.**
- ✓ **Rapid combustion of the premixed fuel-air mixture resulted in high heat release**







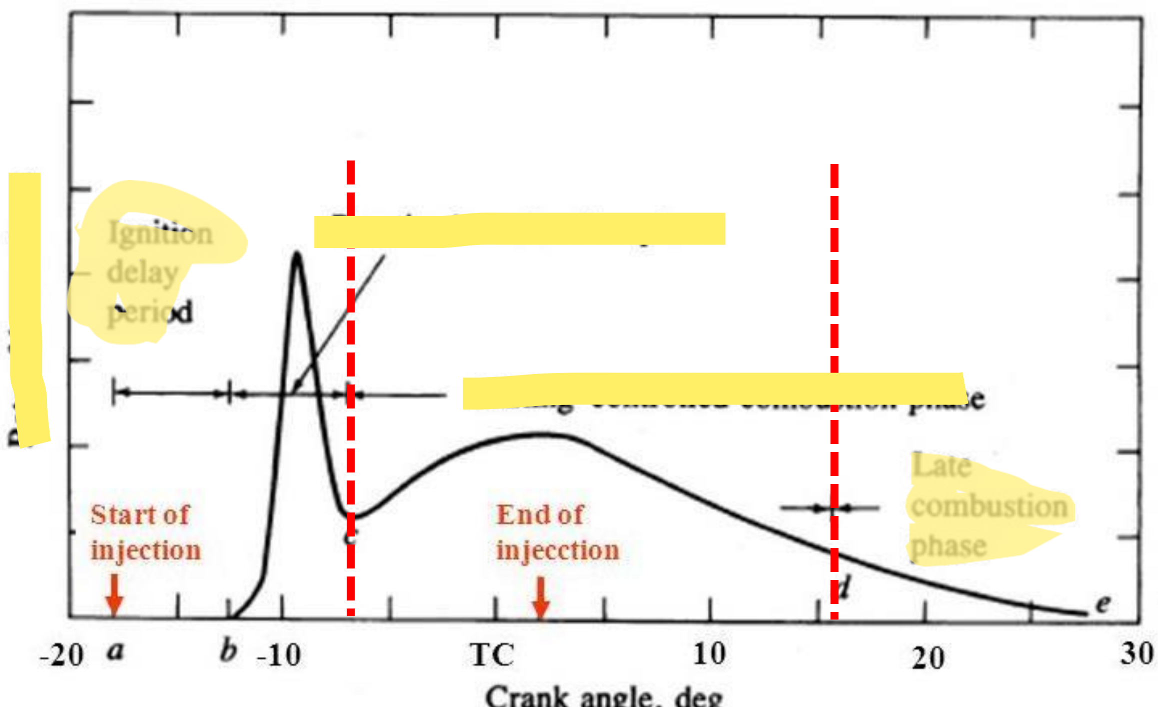
- **Week 09**

Combustion in CI engines

Stages of Combustion

Mixing controlled combustion

- ✓ Rest of the combustion process is controlled by the rate at which fuel can be injected, atomized, vaporized, and mixed into the proper A/F
- ✓ Heat release rate may or may not reach second peak (usually lower peak)

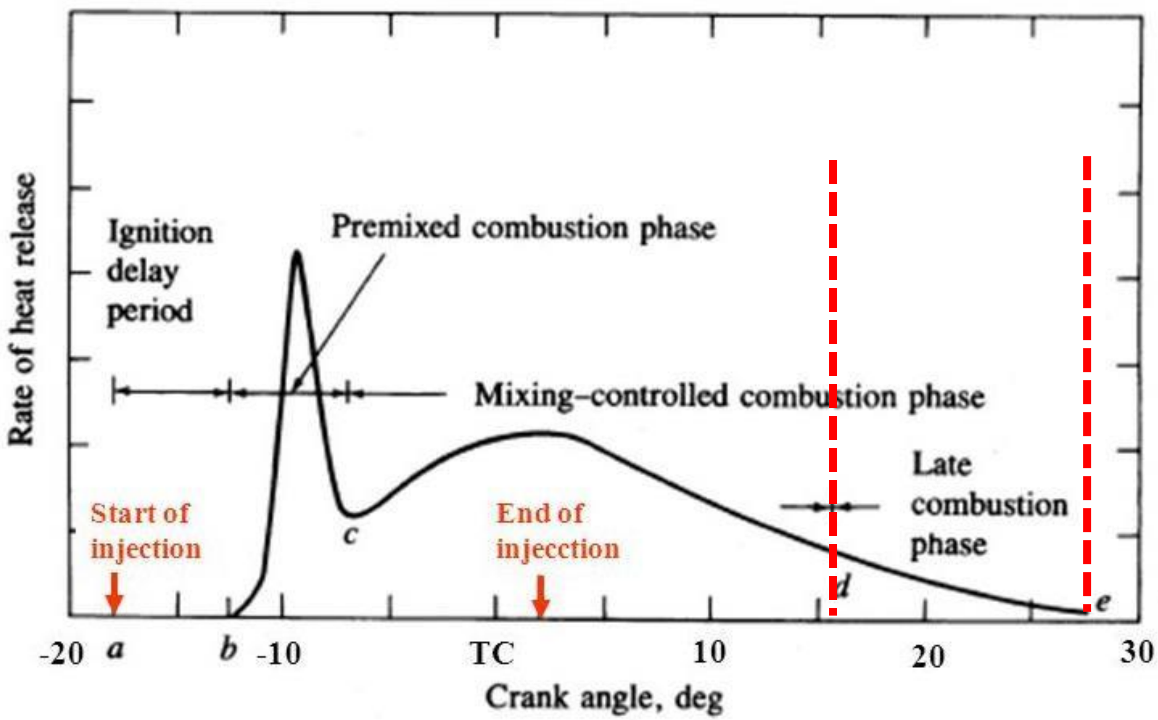


Combustion in CI engines

❑ Stages of Combustion

Late combustion

- ✓ Combustion terminates when the last fuel droplets are reacted after evaporating and mixing with air to form a combustible mixture
- ✓ Heat release continues at a lower rate well into expansion stroke
- ✓ A fraction of fuel may remain unburned, a fraction of fuel energy is present in the soot and the fuel rich combustion products



Combustion in CI engines

❑ Stages of Combustion

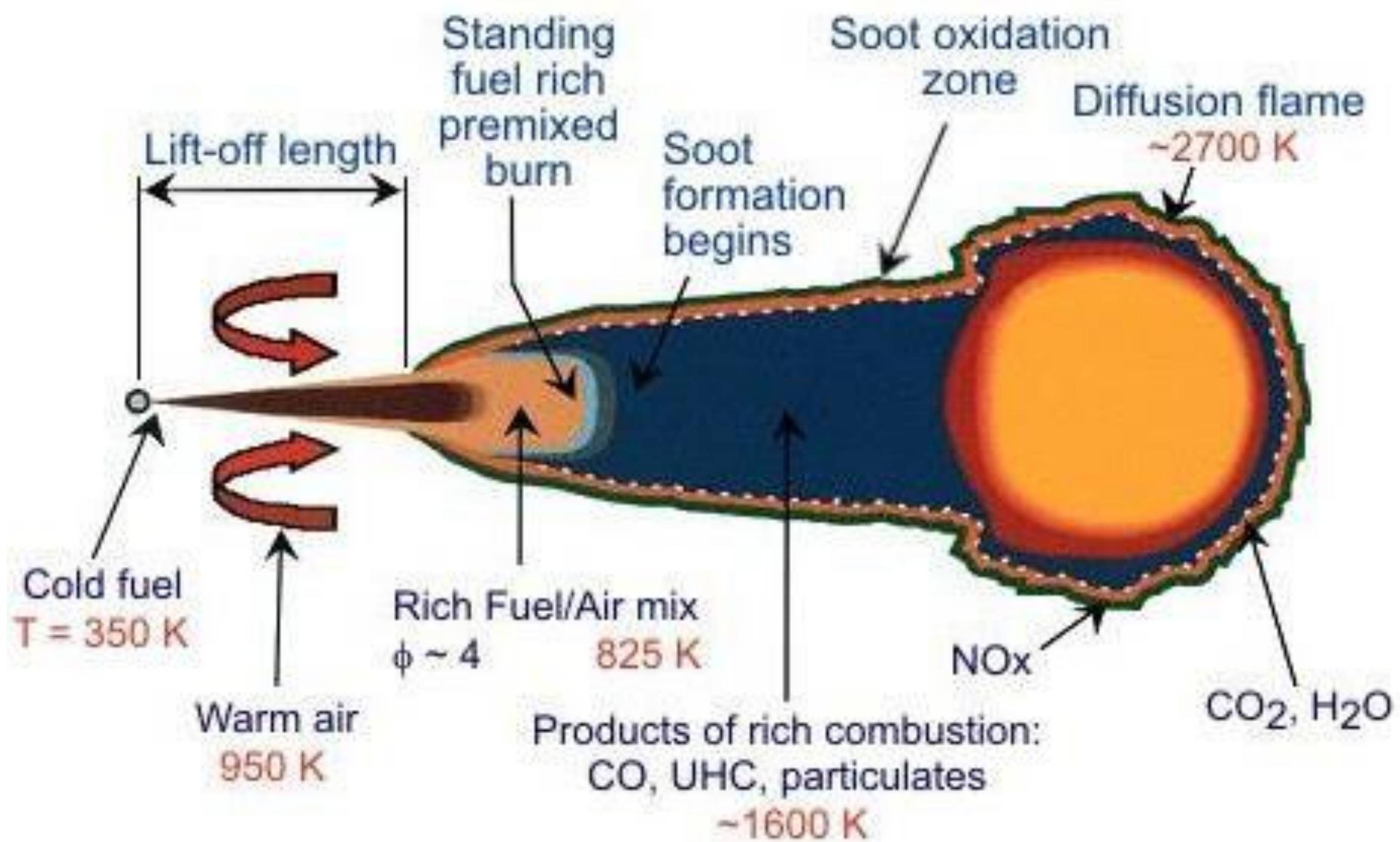
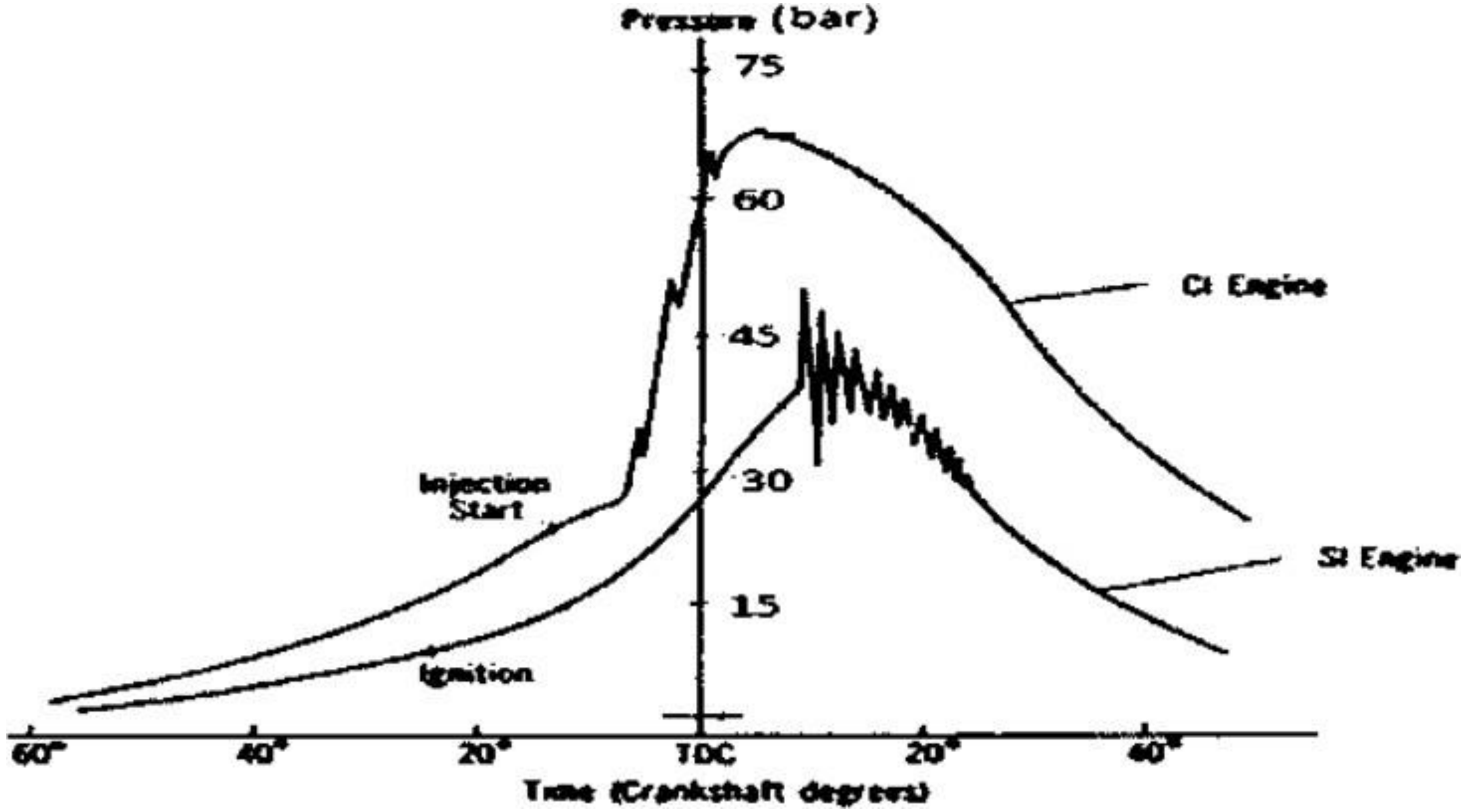


Figure 8. Conceptual Model of Mixing-Controlled Burn Phase

Knocking in CI engines



Knocking in CI engines

❑ Factors affecting knock

➢ **Temperature factors:**

- ✓ **Lowering the compression ratio;**
- ✓ **Lowering the inlet air temperature,**
- ✓ **Lowering the coolant temperature: delay period increases**
- ✓ **Lowering the temperatures of the cylinder and combustion chamber walls: decreasing engine load**
- ✓ **Advancing the start of injection from optimum timing**