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# **Advanced Powertrain Engineering MMME4066 Performance and Efficiency**

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Introduction to operating characteristics and geometric properties

Engine performance parameters and efficiency.

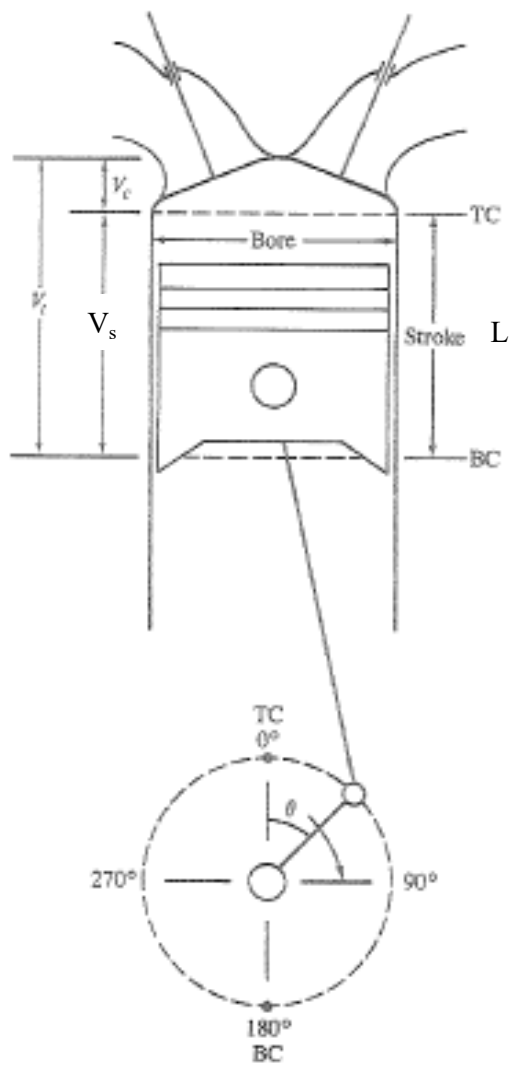
Factors important to engine users.

Enhance your critical thinking using worked examples and problem-solving activities

monitoring student  
attendance

QR code will change at each  
lecture

# Geometrical properties of reciprocating engines



Swept volume,  $V_s$

Volume displaced by piston as it travels through 1 stroke

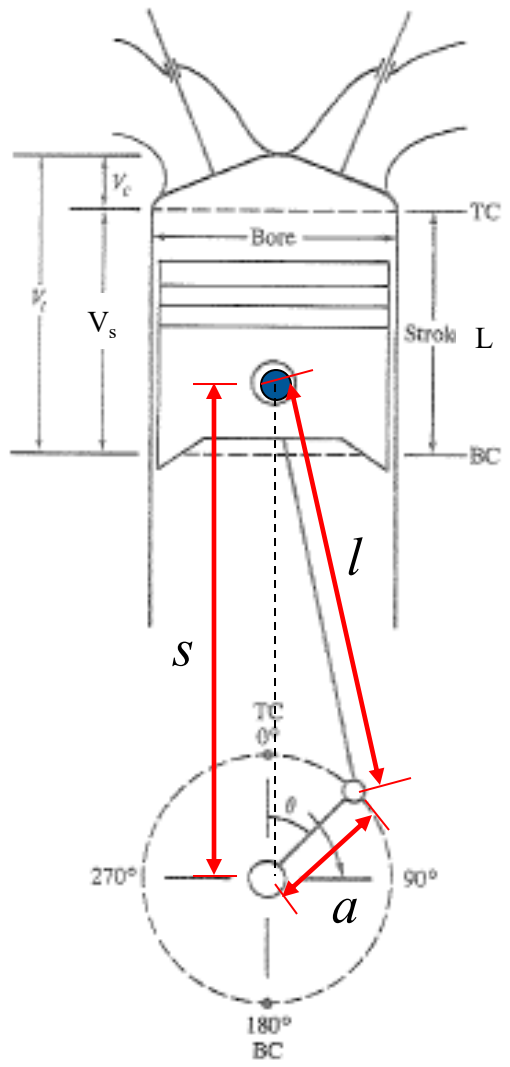
$$V_s = \frac{\pi B^2}{4} L$$

Compression ratio: ratio of the maximum to the minimum volumes

$$Cr = \frac{V_s + V_c}{V_c}$$

Clearance volume ( $V_c$ ) is the volume remaining in the cylinder when the piston is at TDC.

# Geometrical properties of reciprocating engines



Piston position at any crank positions,  $\vartheta$ , is:

$$s = a \cos \vartheta + \left( l^2 - a^2 \sin^2 \vartheta \right)^{1/2}$$

Cylinder volume at any crank positions  $\vartheta$ ,  $V$

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

Piston velocity is  $S = ds/dt$ :

Average/mean piston speed  $S_p$  [m/s],

$$S_p = 2LN$$

Simple and useful

with  $N$  is the crankshaft rotational speed  $N$  [rev/s]



Compression ratio:

SI – 9-12

CI – 14-20

B/L – 0.8-1.2 small and medium size engines

B/L – 0.5 large low speed CI engines

Ford puma cylinder diesel compression ratio (15.5-18.4) and square engine (B=L) with bore 86mm

Oversquare vs undersquare refers to the Bore/Stroke ratio of an engine. If the bore is larger than the stroke, the engine is considered to be oversquare.

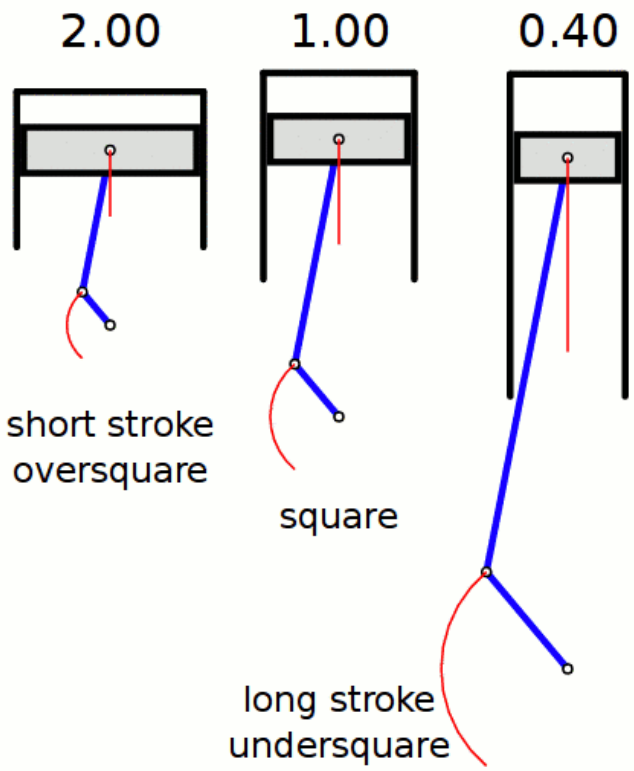
Square:  $B/L=1$

Oversquare  $B/L>1$

Undersquare  $B/L<1$

# B/L impact on performance

bore/stroke ratio



High Performance B/L=??

Efficiency B/L=??

Larger bore allows for larger valves to be used (but heat loss increases).

Shorter stroke allows for a lower piston speed for a given engine speed.

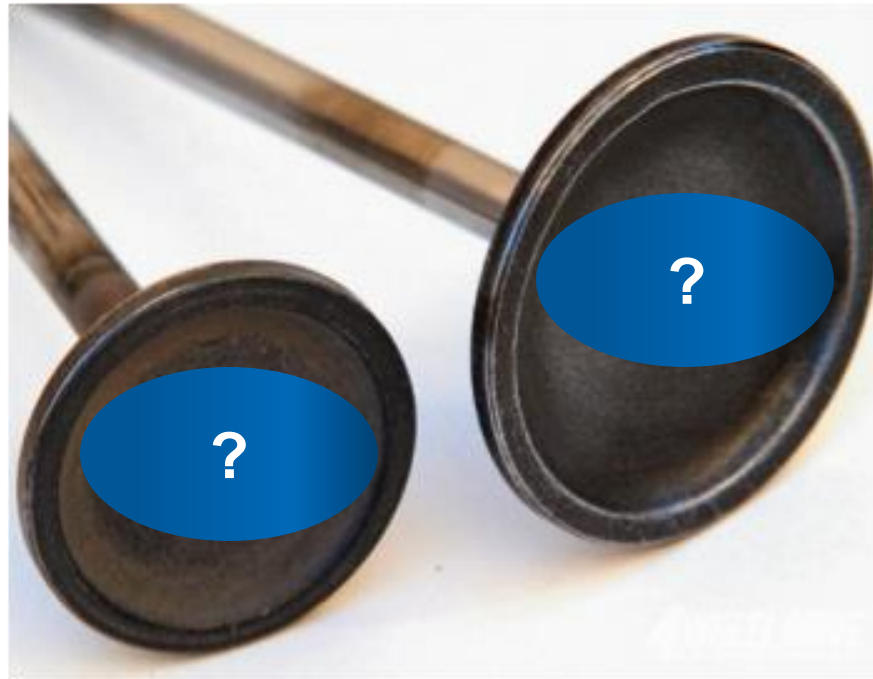


## Worked example (page 11)

Calculate the mean piston speed for a square cylinder for a 3 litre, V6 engine running at 6000rev/min.

## Problem-solving activity (2 minutes)

**Is the exhaust valve smaller or bigger than the intake valve?**

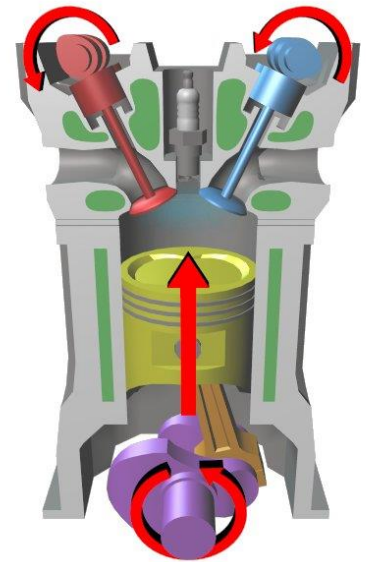




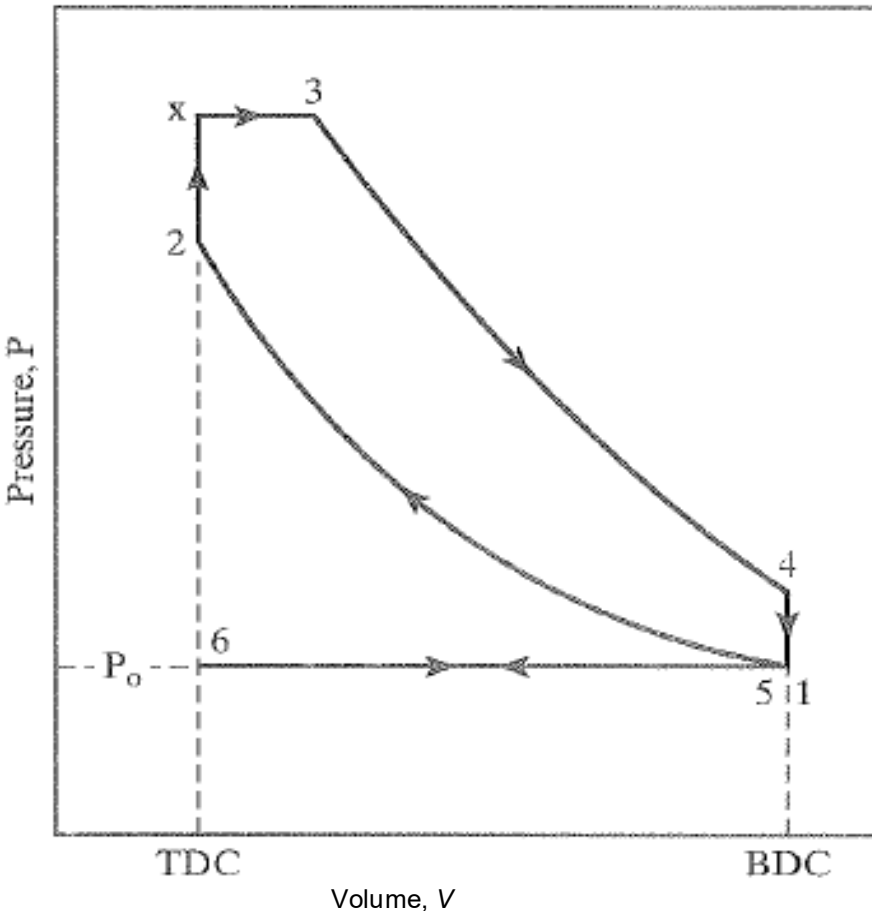
# Problem-solving activity (2 minutes)

## MM1TF1 – thermodynamic cycle

1. The working fluid is modified by combustion and then replaced by fresh charge each time a cycle is completed
2. Air (or air and fuel) is induced into the cylinder
3. The charge is then compressed to high pressure and temperature
4. Charge is ignited and burn releasing energy from fuel
5. Temperature and pressure raise still higher
6. During expansion the internal energy of product of combustion is converted into work
7. Then cylinder gas are expelled into the exhaust



- Ideal air-standard cycle assumptions



6-1 (Intake): Adiabatic constant pressure process

1-2 (Compression) and 3-4 (Expansion): Isentropic processes

2-3 (Combustion –heat addition):  
Combustion is complete

Constant volume processes (SI)  
Constant pressure process (CI)

4-5 (Blowdown –heat rejection):  
Constant volume process

5-6 (Exhaust) Adiabatic constant pressure processes

Only during the compression and expansion strokes of the cycle the cylinder is a closed system. This part of the cycle can be represented by ideal thermodynamic cycles: e.g. Otto and Diesel

For simplifications, ideal thermodynamics air-standard cycles are used to model individual processes undergone by the operating cycle of ICEs.

ICEs are not heat engines in the thermodynamic definition of the term:

- Working fluid does not complete a closed cycle
- Does not exchange heat with 2 reservoirs
- Peak efficiency does not always coincide with peak temperature ( confirming departure from heat engine characteristics)

”The use of the theory of the heat engine as a vehicle for explaining the {internal combustion engine} should be seen as a device to aid teaching by simplifying. But in the process of simplifying, some important points get lost.” John Clarke, Caterpillar, 1983.

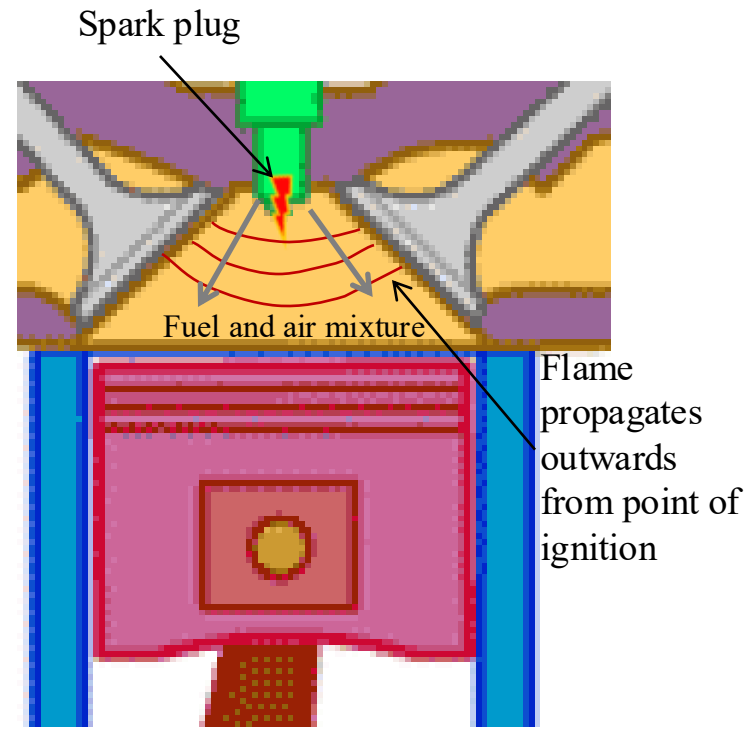
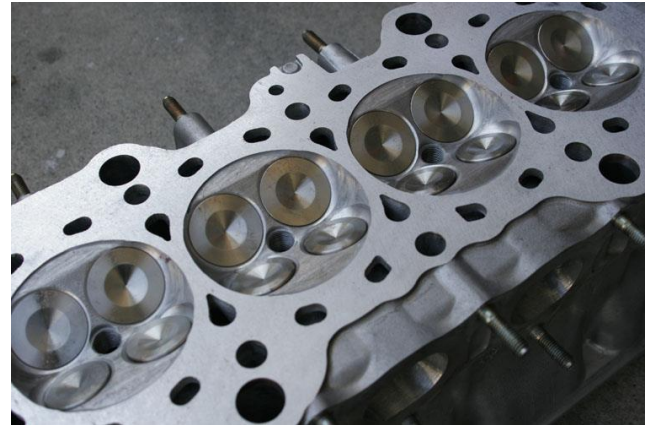
Combustion chamber: typically pent-roof

## Homogeneous combustion

- Air/fuel premixed outside the cylinder (except DISI)
- Spark ignites the mixture
- Combustion rate is controlled by the flame propagation
- Intake throttle to regulate quantity of charge (quantity controlled)
- Compression ratio typically 10:1 ( avoid charge starting to burn too early)

## Work output

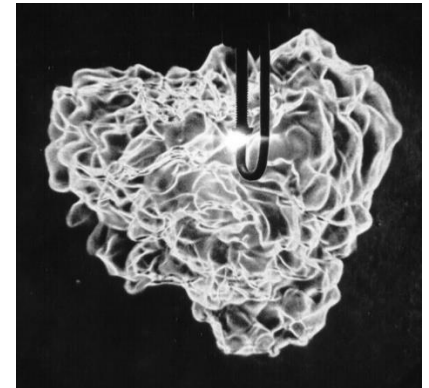
- Quantity governed – quantity of air and fuel regulated
- AFR is constant at stoichiometric value (14.7) for most conditions



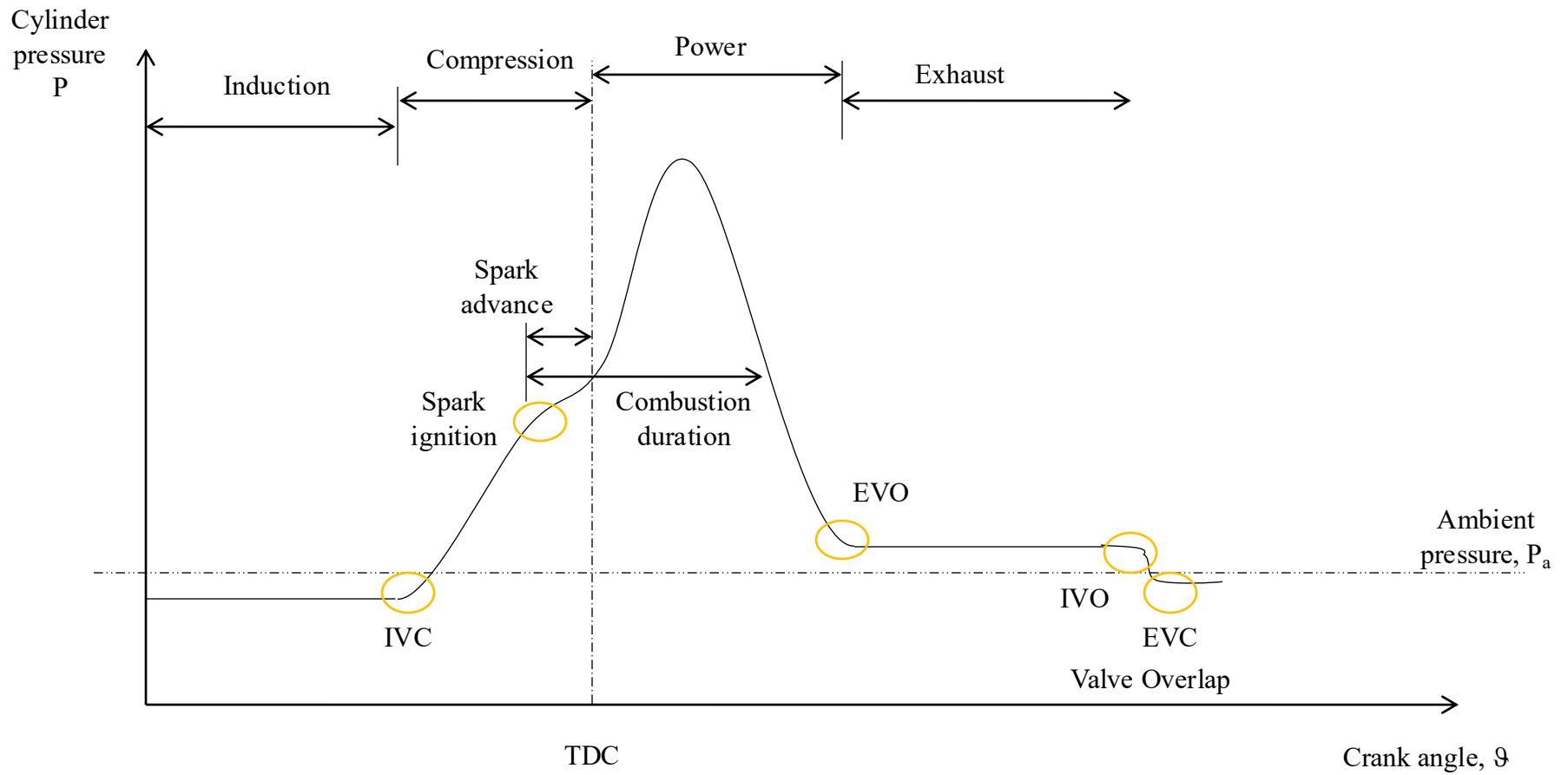


# SI engine- essential features of process

- Air/fuel premixed outside the cylinder (except DISI)
- Air/fuel mixture inducted through intake valve into cylinder
- Air and fuel mix with residual gas takes place
- Mixture is compressed
- Combustion is initiated towards end of comp. stroke
- Turbulent flame develops
- Flame propagates through a premixed fuel, air, burned gas mix
- Flame reaches the cylinder wall and extinguishes
- Exhaust stroke

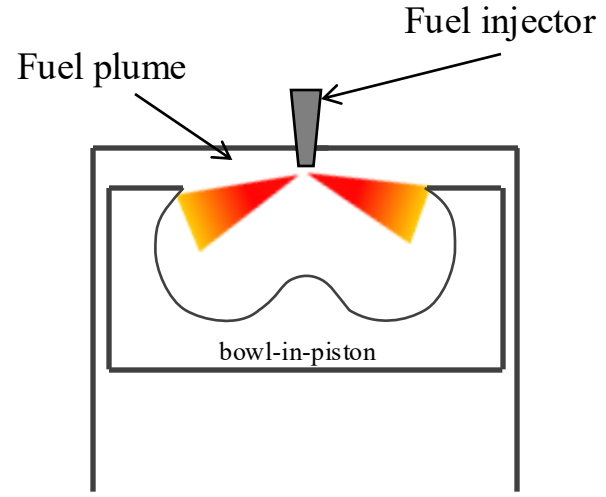


# Pressure vs Crank Angle, SI engine



Stages of SI Combustion will be discussed later– Heat release and Combustion lecture

## Combustion chamber: bowl-in-piston



## Heterogeneous combustion

- Fuel injected late in the compression stroke
- Auto ignition occurs due to high compression temperature/pressure
- Rate of fuel and air mixing controls the combustion rate

## Work output

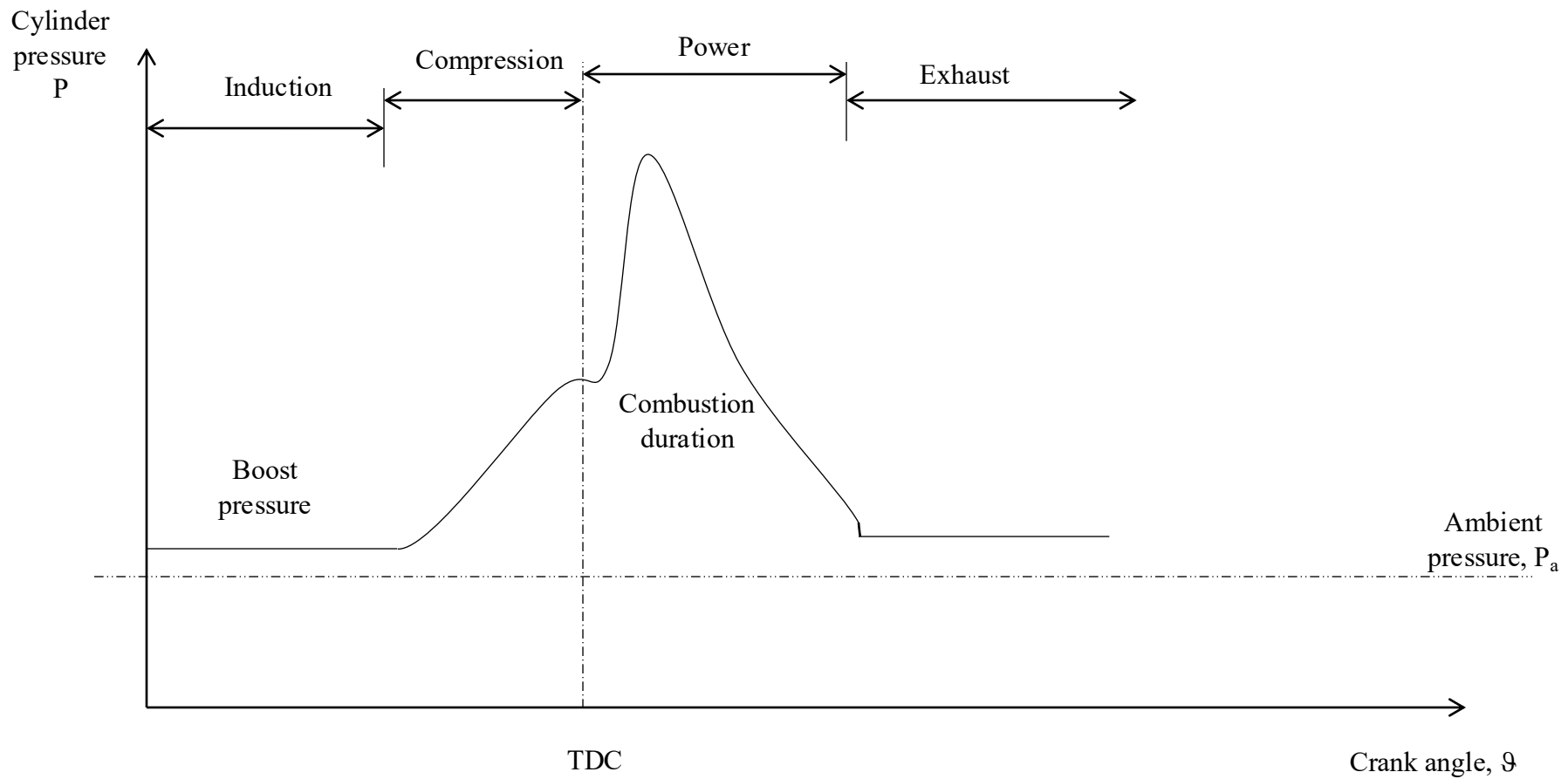
- Quality governed - fuel injected regulated to change work output; air not regulated
- AFR changes over time

# CI engine- essential features of process

- Air inducted through intake valve into cylinder
- Fuel is injected into the cylinder by the FIE towards end of comp. stroke
- Fuel atomizes in small drops and vaporizes (delay period prior ignition)
- Spontaneous ignition of portions of already-mixed air and fuel (P & T above auto ignition point)
- Mixed fuel air burn rapidly
- Injection continues until desired amount of fuel has entered the chamber.
- Combustion rate driven by the rate of fuel and air mixing and continues during expansion stroke



# Pressure vs Crank Angle, CI engine



Stages of CI Combustion will be discussed later – Heat release and Combustion lecture

Pressure data for the gas in the cylinder over the operating cycle can be used to calculate the work transfer from gas to piston.



Cylinder Pressure Sensor for Engine Monitoring

Cylinder pressure is measured on real time consecutive cycles and pressure transducer is installed on the cylinder head



A crank angle encoder is also installed on the engine to and provides precise crank-angle position measurements.

This information was then routed to a high speed data acquisition system.



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# Part 2



Introduction to operating characteristics and geometric properties/parameters.

Factors important to engine users.

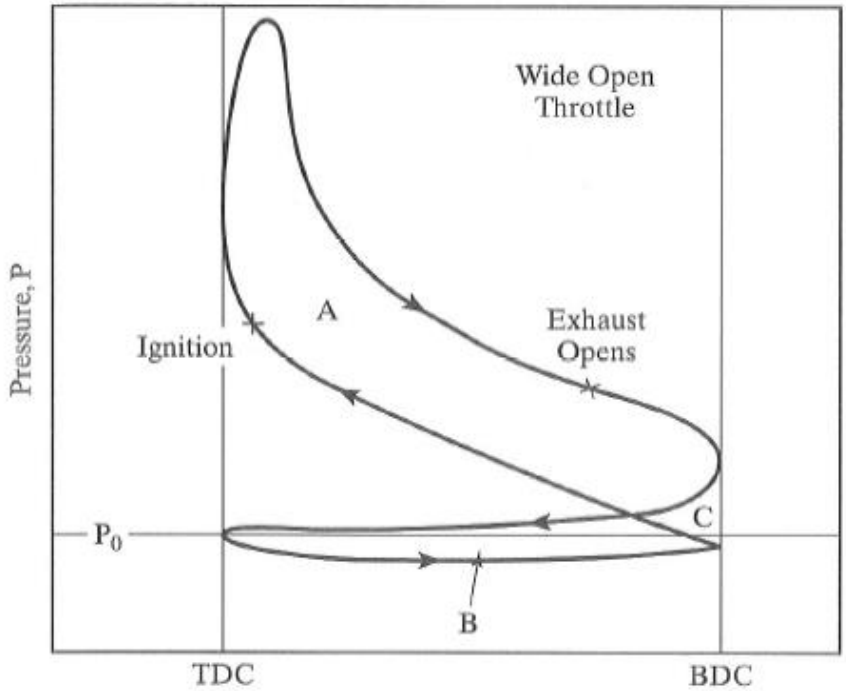
Enhance your critical thinking using worked examples and problem-solving activities

# Indicated Work

Output of any heat engine and in ICE, is generated by in-cylinder working fluid (gasses)

Result of force due to gas pressure acting through the distance in which the piston moves

Can be obtained through an engine cycle plotted on a  $p - V$  coordinates (indicator diagram) – indicated work



$$W_i = -\oint p dV$$

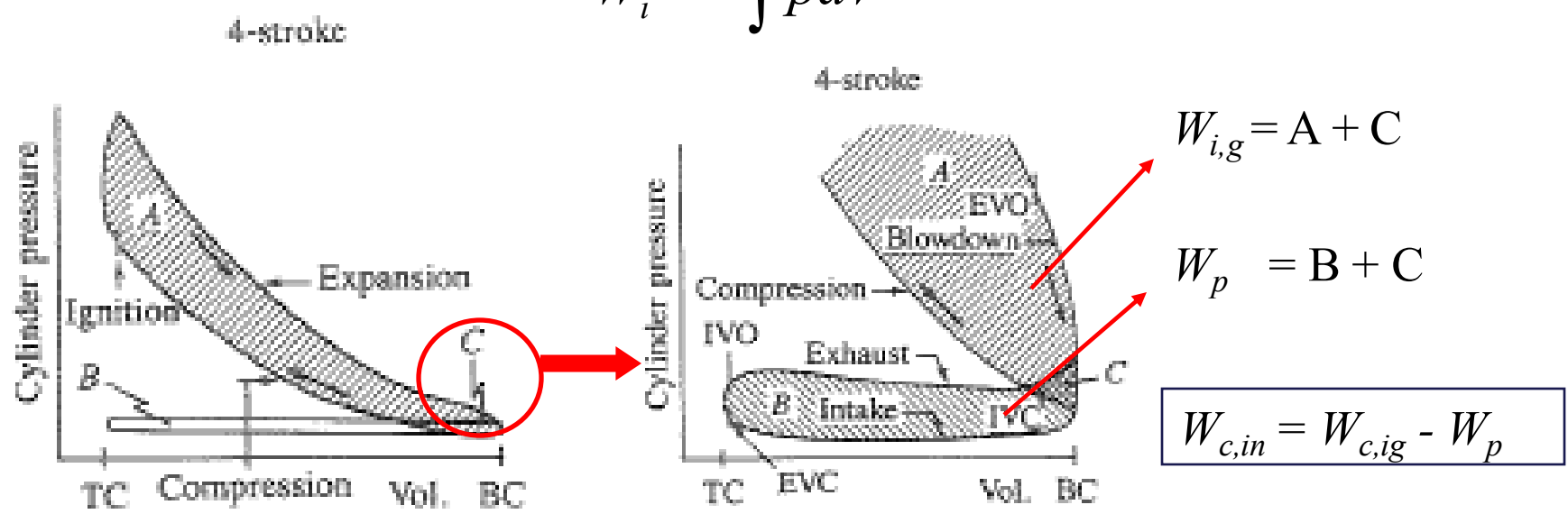
# Indicated work per cycle (per cylinder)

**Gross indicated work per cycle (per cylinder)  $W_{c,ig}$**  work delivered to piston over compression and expansion strokes only

**Net indicated work per cycle (per cylinder)  $W_{c,in}$**  work delivered to piston over the entire 4-stroke cycle

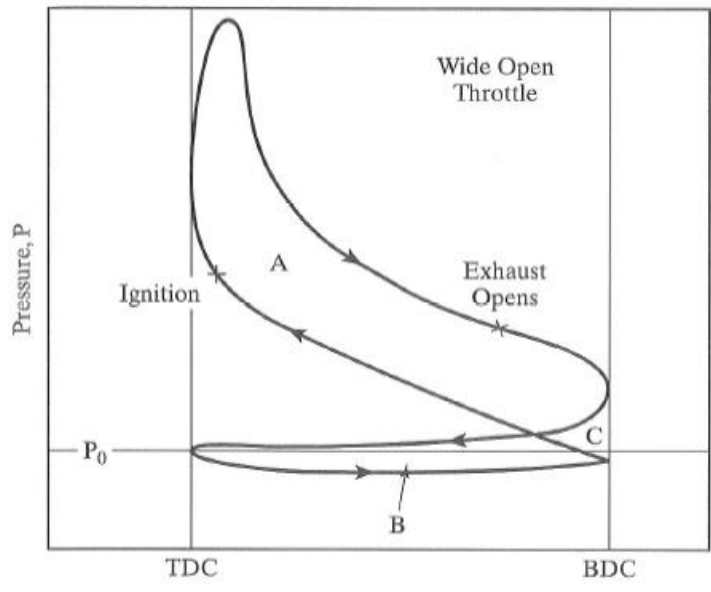
Indicated work per cycle (per cylinder) can be obtained by integrating over the cycle

$$W_i = -\oint pdV$$



# Indicated work per cycle (per cylinder)

## Naturally aspirated engines

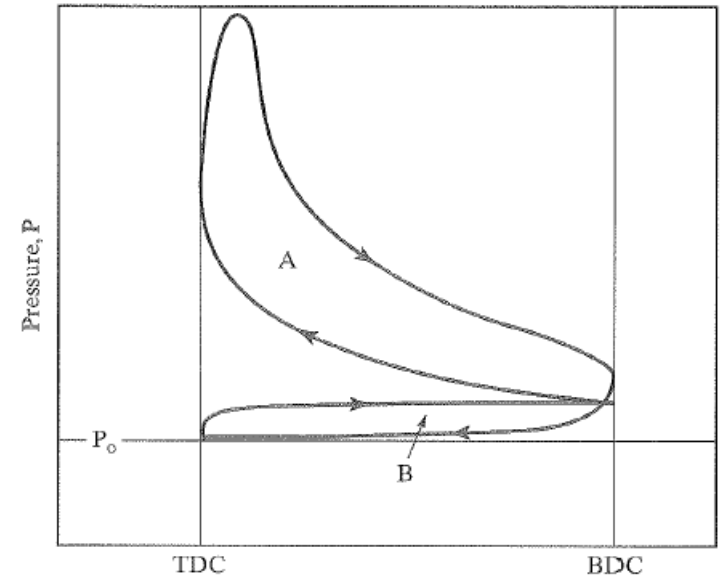


Pumping work transfer to working fluid if pressure during intake less than pressure during exhaust

Negative pumping work

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

## Supercharged/Turbocharged engines



Pumping work transfer from working fluid to piston if pressure during intake more than pressure during exhaust

Positive pumping work

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



Ratio of the work produced per cycle to the amount of fuel energy supplied per cycle to be released

$$\eta_f = \frac{W_{c,ig}}{m_f Q_{LHV}}$$

$$\eta_f = \frac{\dot{W}_{c,ig}}{\dot{m}_f Q_{LHV}}$$

A measure of engine efficiency

Typical heating values for gasoline and diesel are in the range 42-44 MJ/kg



Fraction of fuel that combusts. Ratio of the heat released per cycle to the amount of fuel energy supplied per cycle to be released

$$\eta_c = \frac{Q_{in}}{m_f Q_{LHV}}$$

Useful expression which fits a large body of data covering SI and CI engine:

$$\eta_c = 0.94(1 - \ln \phi) \quad \text{or} \quad 98\%, \text{ whichever is lower}$$

$\phi$  Equivalence ratio defines the mixture composition



It indicates how well the heat released is converted into work

$$\eta_{i,g} = \frac{W_{c,ig}}{Q_{in}}$$

Given that:

$$\eta_{i,g} = \frac{W_{c,ig}}{\eta_c m_f Q_{LHV}}$$

It results:

$$\eta_{i,g} \eta_c = \frac{W_{c,ig}}{m_f Q_{LHV}} = \eta_f$$



## Worked example (page 27)

Show that gross isfc is given by  $\text{gross isfc} = \frac{1}{\eta_f Q_{LHV}}$



Only part of the gross indicated work is transferred to the output shaft (brake work). Losses reduce the useful work output. The ratio between of brake to indicated power is called mechanical efficiency ( $\eta_m$ )

Mechanical efficiency depends on throttle position, engine design and speed.

Typically, mechanical efficiency is at 90% at full throttle for speed around 1800 to 2400 rpm. This decreases to 75% at maximum rated speed.

**Friction:** frictional resistance at rubbing surfaces in engine

**Ancillaries:** e.g. work needed for oil and water pumps

**Pumping:** induct and exhaust gas from cylinder

Net Work

$$W_{c,ig} = W_p + (W_f + W_a + W_b)$$

$$\text{gross } isfc = \frac{\dot{m}_f}{\dot{W}_{c,ig}} \quad \text{Lower than} \quad bsfc = \frac{\dot{m}_f}{\dot{W}_b}$$



We defined indicated work, gross and net

We introduced the concept of combustion efficiency, fuel conversion efficiency, thermal efficiency and mechanical efficiency

Worked example to nail down the concepts

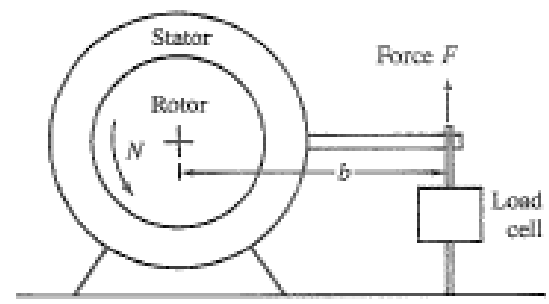


# Summary

- We discussed some geometrical relationships and some of the parameters typically used to characterise engine operation.
- We looked at bore to stroke ratio and linked to engine performance
- Encouraged you to enhance the critical thinking using problem-solving activities

# Torque (brake)

**Torque:** Excellent measurement of engine's ability to do work, but depends on engine size (larger engine will have larger torque)



$$T = Fb$$

Measured using a dynamometer – engine is clamped on a test bed + shaft connected to dynamometer rotor

Units

$$N \cdot m$$

# Power (brake)

Measurement of the rate at which work is done. It depends on speed.

Power delivered by engine is product of torque and angular speed

Brake power: Power transferred from engine to the output shaft

$$\dot{W}_b = 2\pi NT$$

Units  
*W*

Power per cylinder can be related to the work per cycle by:

$$\dot{W}_b = \frac{W_b N}{n_R}$$

$n_R$  is number of crank revolution for each power stroke per cylinder.  
 $n_R = 2$  for 4-stroke and 1 for 2-stroke

My old car used to be a 2.0 Litre diesel 94 kW; (126 hp) @ 3,800rpm

My new car 125hp and 170Nm peak torque between 1,400 and 4,500rpm with CO2 emissions of 114g/km



# Brake Specific Fuel Consumption

Fuel flow rate per unit of power output:

$$bsfc = \frac{\dot{m}_f}{\dot{W}_b} \quad \begin{array}{l} \text{Units} \\ \frac{g}{kW h} \end{array}$$

It is a measure of how efficiently an engine uses the fuel supplied to produce work

Low values desirable

SI engine 2000-3000rpm @ 90% of full load                      240g/kWh

Diesel 1500-2000rpm    210g/kWh

Under idling conditions no brake power output but still fuel is consumed  
Idle fuel consumption is given as g/h

Common to use fuel economy in terms of distance travelled per unit of fuel  
(e.g. miles per gallon (mpg) or litres per 100 km.



**Brake Specific Fuel Consumption** (how efficiently an engine uses the fuel supplied to produce work)

$$bsfc = \frac{\dot{m}_f}{\dot{W}_b}$$

Units

$$\frac{g}{kWh}$$

$$\text{gross isfc} = \frac{\dot{m}_f}{\dot{W}_{i,g}}$$

**Gross indicated work** per cycle (per cylinder)  $W_{c,ig}$  work delivered to piston over compression and expansion strokes only

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Brake torque per cylinder can be related to brake work per cycle by:

$$\dot{W}_b = \frac{W_b N}{n_R} \quad \dot{W}_b = 2\pi N T \quad \frac{W_b N}{n_R} = 2\pi N T$$

$$T = \frac{W_b}{2\pi n_R}$$

A portion of the gross indicated work is used to overcome friction, induct fresh charge and drive other mechanical components

$$W_b = W_{c,ig} - (W_p + W_a + W_f)$$

- Power to induct fresh charge and expel exhaust gases
- Power to drive engine accessories
- Power to overcome friction of bearings, pistons, other mechanical components

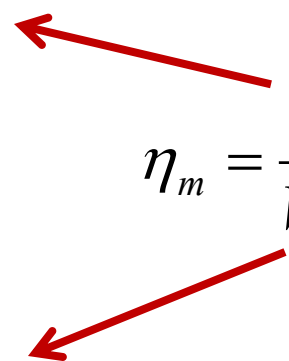


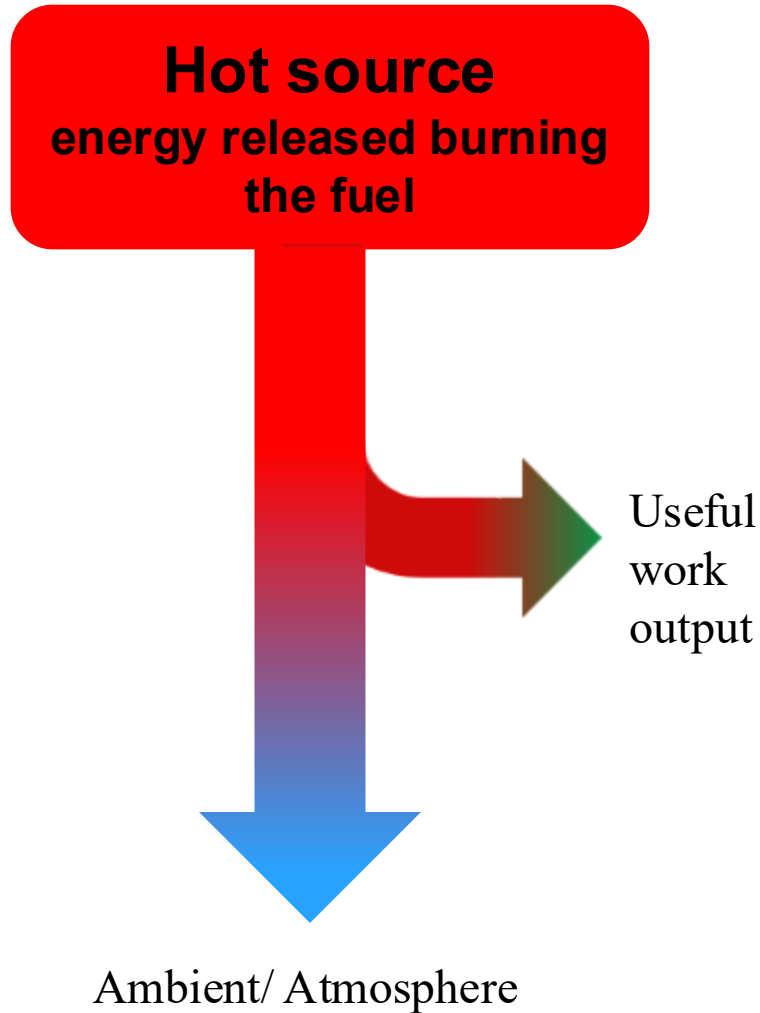
Specific fuel consumption (sfc) is the fuel flow rate per unit power output

$$bsfc = \frac{\dot{m}_f}{\dot{W}_b} \qquad \text{gross isfc} = \frac{\dot{m}_f}{\dot{W}_{i,g}}$$

Depending on the definition of power, there are bsfc, isfc (gross/net), fsfc and psfc.

In addition,

$$\dot{W}_b = \frac{\dot{m}_f}{bsfc}$$
$$\eta_m = \frac{\dot{W}_b}{\dot{W}_{i,g}} = \frac{isfc}{bsfc}$$
$$\dot{W}_{i,g} = \frac{\dot{m}_f}{isfc}$$




Max energy stored in the fuel

$$m_f Q_{LHV}$$

Not all the heat input would  
go into useful work output

Typical efficiencies?



Ratio of the work produced per cycle to the amount of fuel energy supplied per cycle to be released

$$\eta_f = \frac{W_{c,ig}}{m_f Q_{LHV}}$$

A measure of engine efficiency

$$\eta_f = \frac{\dot{W}_{c,ig}}{\dot{m}_f Q_{LHV}}$$

Typical heating values for gasoline and diesel are in the range 42-44 MJ/kg



Fraction of fuel that combusts. Ratio of the heat released per cycle to the amount of fuel energy supplied per cycle to be released

$$\eta_c = \frac{Q_{in}}{m_f Q_{LHV}} \quad \text{Typical value 98\%}$$

Useful expression which fits a large body of data covering SI and CI engine:

$$\eta_c = 0.94(1 - \ln \phi) \quad \text{or} \quad 98\%, \text{ whichever is lower}$$

$\phi$  Equivalence ratio defines the mixture composition



It indicates how well the heat released is converted into work

$$\eta_{i,g} = \frac{W_{c,ig}}{Q_{in}}$$

Given that:

$$\eta_{i,g} = \frac{W_{c,ig}}{\eta_c m_f Q_{LHV}}$$

It results:

$$\eta_{i,g} \eta_c = \frac{W_{c,ig}}{m_f Q_{LHV}} = \eta_f$$



# Specific Fuel Consumption

It is a measure of how efficiently an engine uses the fuel supplied to produce work

Fuel flow rate per unit of power :

$$bsfc = \frac{\dot{m}_f}{\dot{W}_b} \quad \text{Units} \quad \frac{g}{kWh}$$

$$isfc = \frac{\dot{m}_f}{\dot{W}_{c,ig}} \quad \text{Units} \quad \frac{g}{kWh}$$

Low bsfc values desirable

SI engine 2000-3000rpm @ 90% of full load 240g/kWh

Diesel 1500-2000rpm 210g/kWh



## Worked example (page 27)

If combustion liberated the lower heating value of the fuel and this was converted entirely into gross indicated work, what is the corresponding gross isfc in g/kW.hr if  $Q_{LHV}$  is 42 or 44 MJ/kg?



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If combustion liberated the lower heating value of the fuel and this was converted entirely into gross indicated work, what is the corresponding gross isfc in g/kW.hr if  $Q_{LHV}$  is 42 or 44 MJ/kg?



- We discussed some of the parameters typically used to characterise engine operation.
- We discussed the factors important to an engine such as the power and torque at each speed, and its fuel consumption within the operating range
- We have also seen that ideal thermodynamics air-standard cycles are used to model individual processes undergone by the operating cycle of ICEs