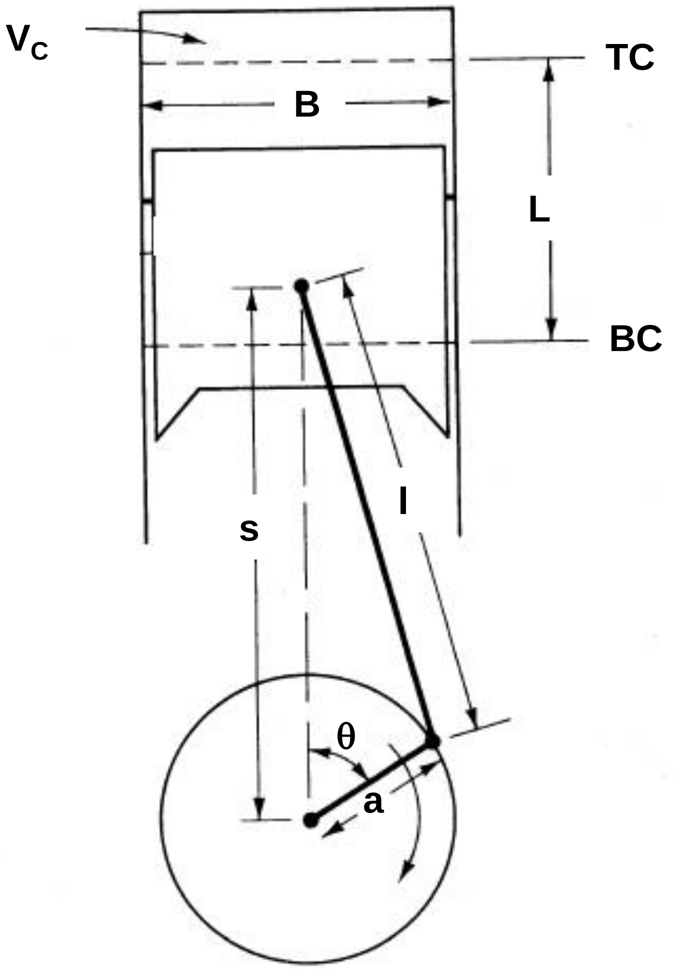
Engine Geometry



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

Cylinder volume when piston at TC (*s*=*l*+*a*) defined as the clearance volume V_c

The cylinder volume at any crank angle is:

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

Maximum displacement, or swept, volume:

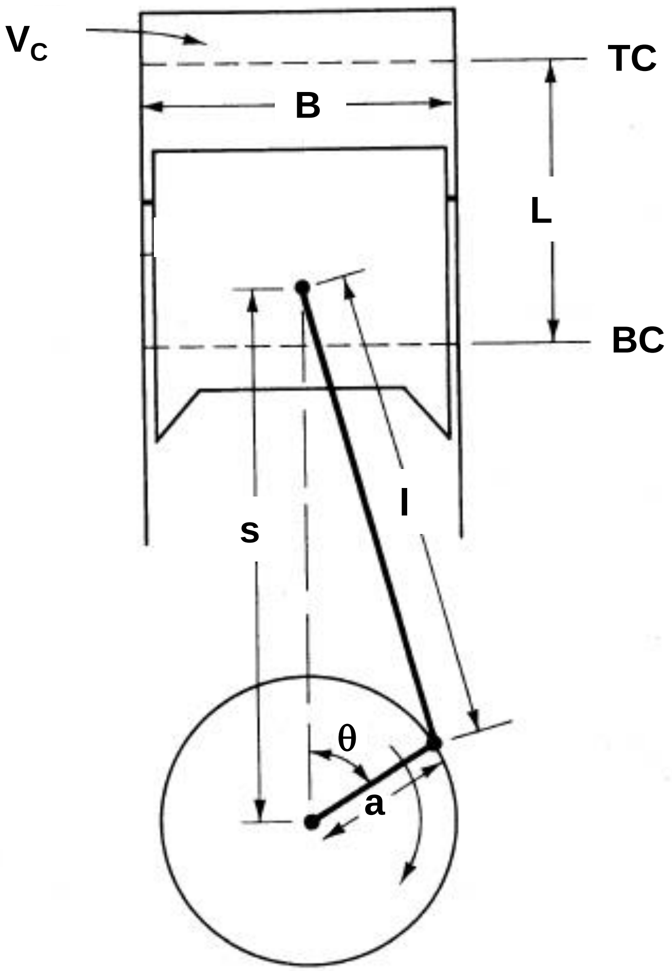
$$V_d = \frac{\pi B^2}{4} L$$

Compression ratio:

$$r_c = \frac{V_{BC}}{V_{TC}} = \frac{V_c + V_d}{V_c}$$

For most engines B ~ L (square engine)

Mean and Instantaneous Piston Speeds



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

Average and **instantaneous** piston speeds are:

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

$$S_p = \frac{ds}{dt}$$

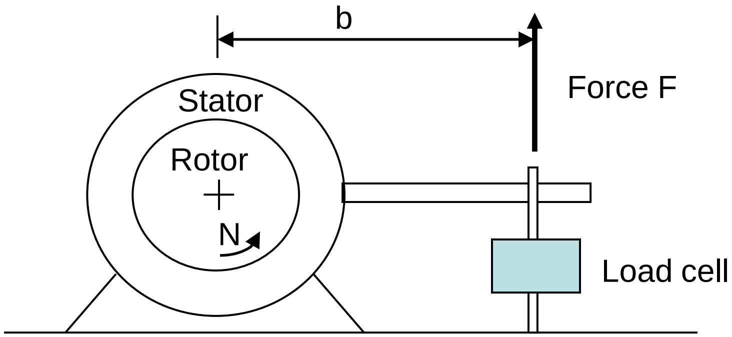
Where N is the rotational speed of the crank shaft in units revolutions per second

$$\frac{S_p}{\overline{S}_p} = \frac{\pi}{2}\sin\theta\left[1 + \frac{\cos\theta}{\left((l/a)^2 - \sin^2\theta\right)^{1/2}}\right]$$

Average piston speed for a standard auto engine is ~15 m/s. Ultimately limited by material strength. Therefore engines with large strokes run at lower speeds those with small strokes can run at higher speeds.

Engine Torque and Power

Torque is measured using a dynamometer.



The **torque** exerted by the engine is: $T = F\,b$ *with units: J*

The **power** P delivered by the engine turning at a speed N and absorbed by the dynamometer is:

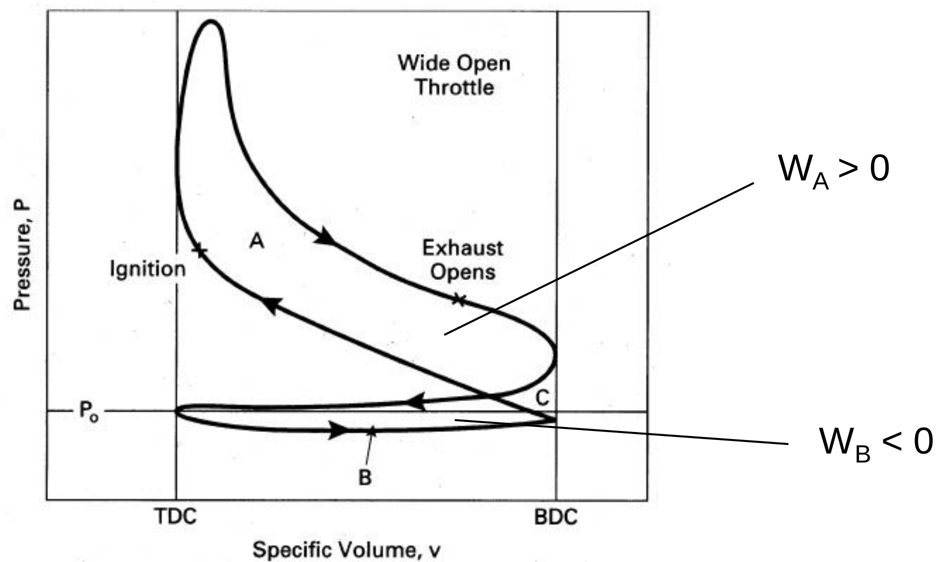
$$P = \omega T = (2\pi N)\,T \quad \text{w/units: (rad/rev)(rev/s)(J) = Watt}$$

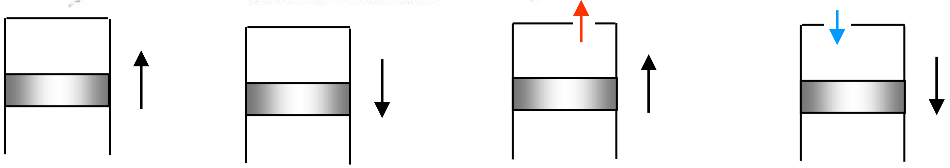
Note: ω is the shaft angular velocity with units: rad/s

Indicated Work

Given the cylinder pressure data over the operating cycle of the engine one can calculate the work done by the gas on the piston.

The indicated work per cycle is $W_i = \oint p dV$





Compression
W<0

Power
W>0

Exhaust
W<0

Intake
W>0

Indicated Power

$P_i = W_i N / n_R$ w/units: (kJ/cycle) (rev/s) / (rev/cycle)

where N – crankshaft speed in rev/s

n_R – number of crank revolutions per cycle

= 2 for 4-stroke

= 1 for 2-stroke

Power can be increased by increasing:

- the engine size, V_d
- compression ratio, r_c
- engine speed, N

Mechanical Efficiency

Some of the power generated in the cylinder is used to overcome engine friction. The **friction power** is used to describe these losses:

$$P_f = P_i - P_b$$

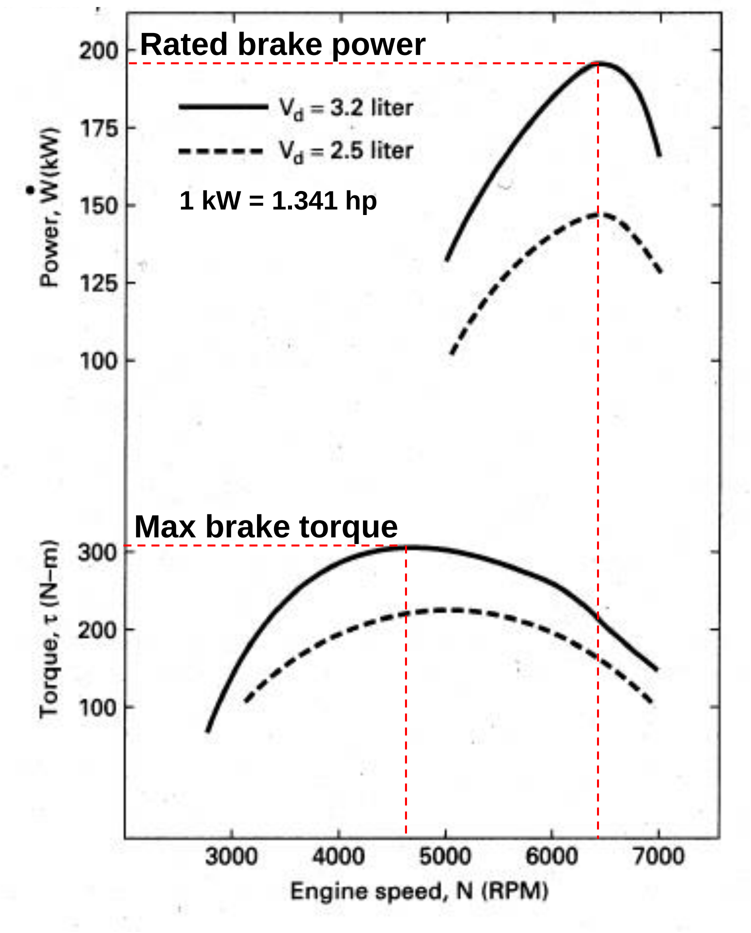
Friction power can be measured by motoring the engine.

The mechanical efficiency is defined as:

$$\eta_m = P_b / P_i = 1 - (P_f / P_i)$$

Mechanical efficiency depends on throttle position, engine design, and engine speed. Typical values for car engines at WOT are 90% @2000 RPM and 75% @ max speed.

Power and Torque versus Engine Speed



There is a maximum in the brake power versus engine speed called the **rated brake power**.

At higher speeds brake power decreases as friction power becomes significant compared to the indicated power

There is a maximum in the torque versus speed called **maximum brake torque** (MBT).

Brake torque drops off:

- at lower speeds do to heat losses
- at higher speeds it becomes more difficult to ingest a full charge of air.

Indicated Mean Effective Pressure (IMEP)

imep is a fictitious *constant* pressure that would produce the same work per cycle if it acted on the piston during the power stroke.

$$imep = W_i / V_d = (P_i\, n_R) / (V_d\, N)$$

so $P_i = imep\, V_d\, N / n_R = imep\, A_p\, U_p / (2\, n_R)$

imep does not depend on engine speed, just like torque.

imep is a better parameter than torque to compare engines for design and output because it is independent of engine speed, N, and engine size, V_d.

Brake mean effective pressure (bmep) is defined as:

$$bmep = \frac{W_b}{V_d} = \frac{2\pi \cdot T \cdot n_R}{V_d} \quad \rightarrow \quad T = \frac{bmep \cdot V_d}{2\pi \cdot n_R}$$

Maximum BMEP

$$bmep = \frac{W_b}{V_d} = \frac{2\pi \cdot T \cdot n_R}{V_d}$$

- The maximum bmep is obtained at WOT at a particular engine speed

- Closing the throttle decreases the bmep

- For a given displacement, a higher maximum bmep means more torque

- For a given torque, a higher maximum bmep means smaller engine

- Higher maximum bmep means higher stresses and temperatures in the engine hence shorter engine life, or bulkier engine.

- For the same bmep 2-strokes have almost twice the power of 4-stroke

Specific Fuel Consumption

- For transportation vehicles fuel economy is generally given as mpg, or liters/100 km.

- In engine testing the fuel consumption is measured in terms of the fuel mass flow rate.

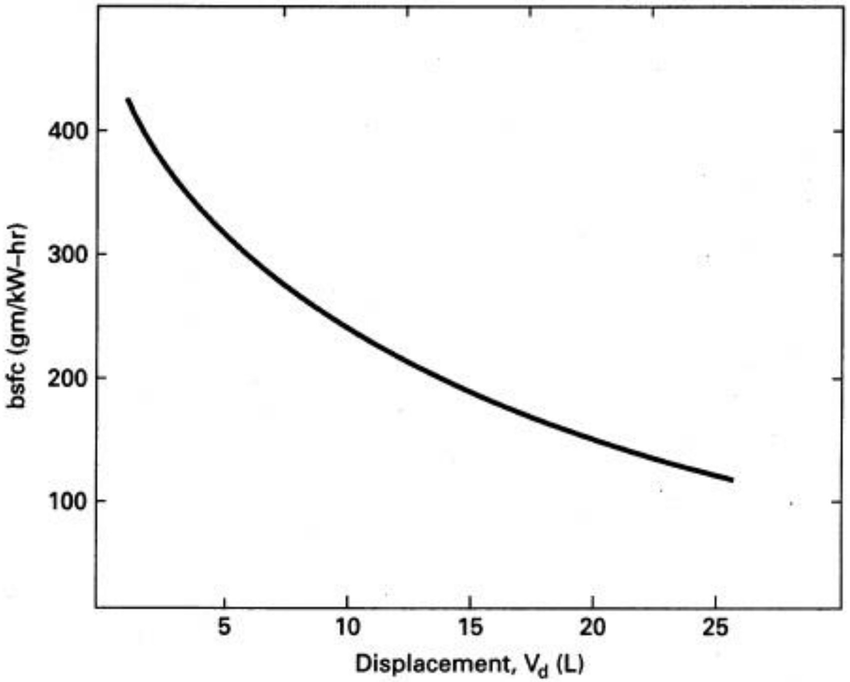
- The **specific fuel consumption,** sfc, is a measure of how efficiently the fuel supplied to the engine is used to produce power,

$$bsfc = \dot{m}_f / P_b \qquad isfc = \dot{m}_f / P_i \qquad \text{(w/units: g/kW-hr)}$$

- Clearly a low value for sfc is desirable since at a given power level less fuel will be consumed

Brake Specific Fuel Consumption vs Size

- BSFC decreases with engine size due to reduced heat losses from gas to cylinder wall.

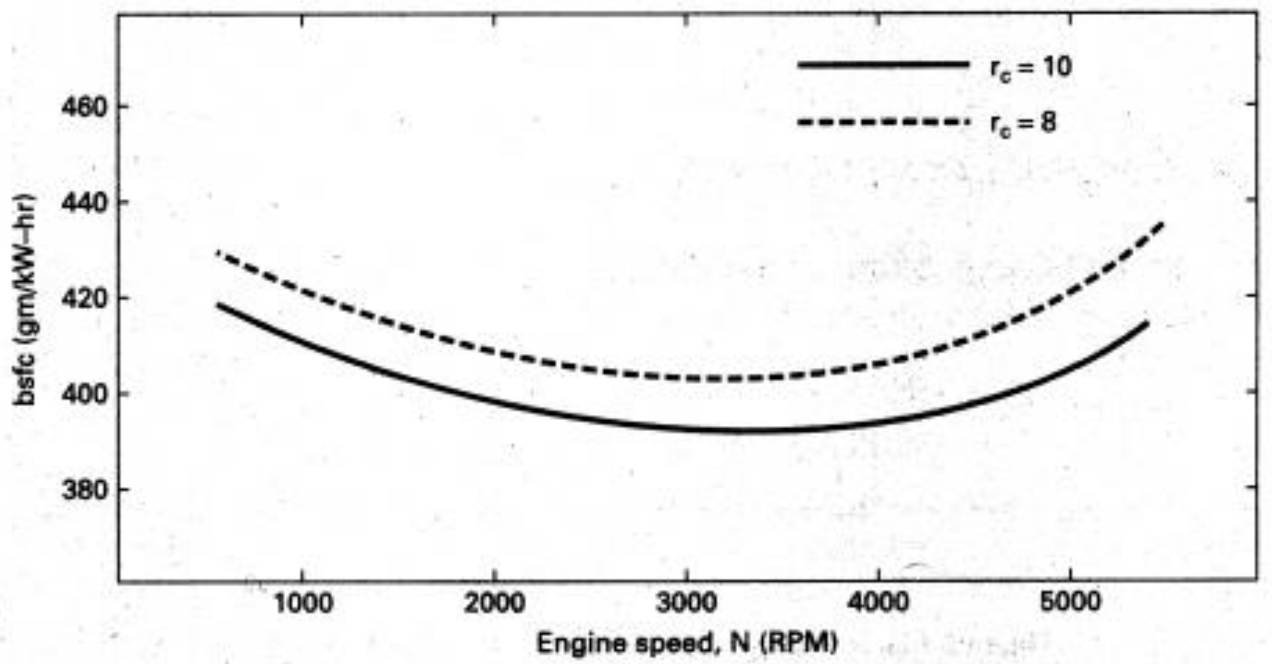


- Note: cylinder surface to volume ratio increases with bore diameter.

$$\frac{cylinder\ surface\ area}{cylinder\ volume} = \frac{2\pi r L}{\pi r^2 L} \propto \frac{1}{r}$$

Brake Specific Fuel Consumption vs Speed

- There is a minimum in the bsfc versus engine speed curve

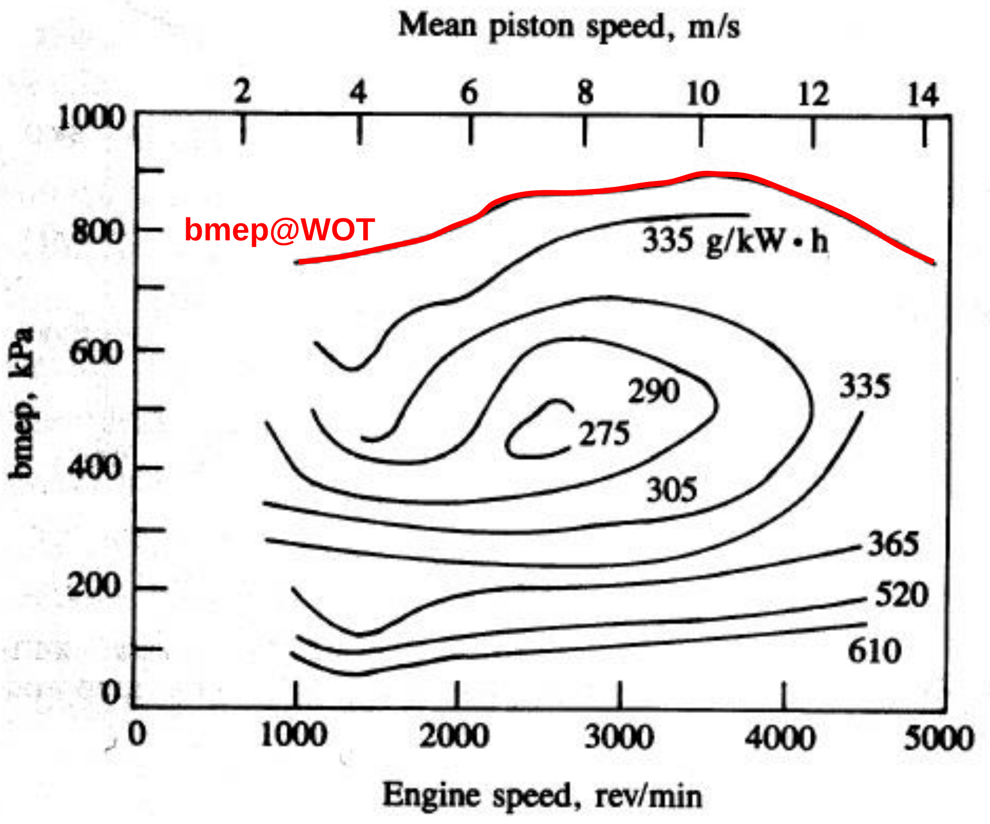


- At high speeds the bsfc increases due to increased friction
- At lower speeds the bsfc increases due to increased time for heat losses from the gas to the cylinder and piston wall
- Bsfc increases with compression ratio due to higher thermal efficiency

Performance Maps

Performance map is used to display the bsfc over the engines full load and speed range. Using a dynamometer to measure the torque and fuel mass flow rate you can calculate:

$$\mathrm{bmep} = 2\pi\, T\, n_R / V_d \qquad P_b = 2\pi\, N\, T$$



$$\mathrm{bsfc} = \dot{m}_f / P_b$$

Constant bsfc contours from a two-liter four cylinder SI engine

Combustion Efficiency

- The time for combustion in the cylinder is very short so not all the fuel may be consumed or local temperatures may not support combustion

- A small fraction of the fuel may not react and exits with the exhaust gas. The **combustion efficiency** is defined as actual heat input divided by theoretical heat input:

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

Where Q_{in} = heat added by combustion per cycle
m_f = mass of fuel added to cylinder per cycle
Q_{HV} = heating value of the fuel (chemical energy per unit mass)

Thermal Efficiency

η_t = work per cycle / heat input per cycle

$$\eta_t = W / Q_{in} = W / (\eta_c\, m_f\, Q_{HV})$$

or in terms of <u>rates</u>…

η_t = power out/rate of heat input

$$\eta_t = P/\dot{Q}_{in} = P/(\eta_c\, \dot{m}_f\, Q_{HV})$$

- Thermal efficiencies can be given in terms of brake or indicated values
- Indicated thermal efficiencies are typically 50% to 60% and brake thermal efficiencies are usually about 30%

Arbitrary Efficiency (aka fuel conversion efficiency)

$$\eta_f = W_b / (m_f\ Q_{HV}) = P_b / (\dot{m}_f\ Q_{HV})$$

Note: η_f is very similar to η_t, the difference is that η_t takes into account only the actual fuel combusted in the engine.

Recall that $sfc = \dot{m}_f / P_b$

Thus $\eta_f = 1 / (sfc\ Q_{HV})$

Volumetric Efficiency

- Due to the short cycle time and flow restrictions less than ideal amount of air enters the cylinder.

- The effectiveness of an engine to induct air into the cylinders is measured by the volumetric efficiency which is the ratio of actual air induced divided by the theoretical air inducted:

$$\eta_v = m_a / (\rho_a V_d) = n_R \dot{m}_a / (\rho_a V_d N)$$

where ρ_a is the density of air at atmospheric conditions P_o, T_o for an ideal gas $\rho_a = P_o / R_a T_o$ and $R_a = 0.287\ kJ/kg\text{-}K$ (at standard conditions $\rho_a = 1.181\ \text{kg/m}^3$)

- Typical values for WOT are in the range 75%-90%, and lower when the throttle is closed

Air-Fuel Ratio

- For combustion to take place, the proper ratio of air and fuel must be present in the cylinder.

- The **air-fuel ratio** is defined as

$$AF = m_a / m_f = \dot{m}_a / \dot{m}_f$$

- The ideal AF is about 15:1, with homogenous combustion possible in the range of 6 to 19.

- For a SI engine the AF is in the range of 12 to 18 depending on the operating conditions.

- For a CI engine, where the mixture is highly non-homogeneous and the AF is in the range of 18 to 70.