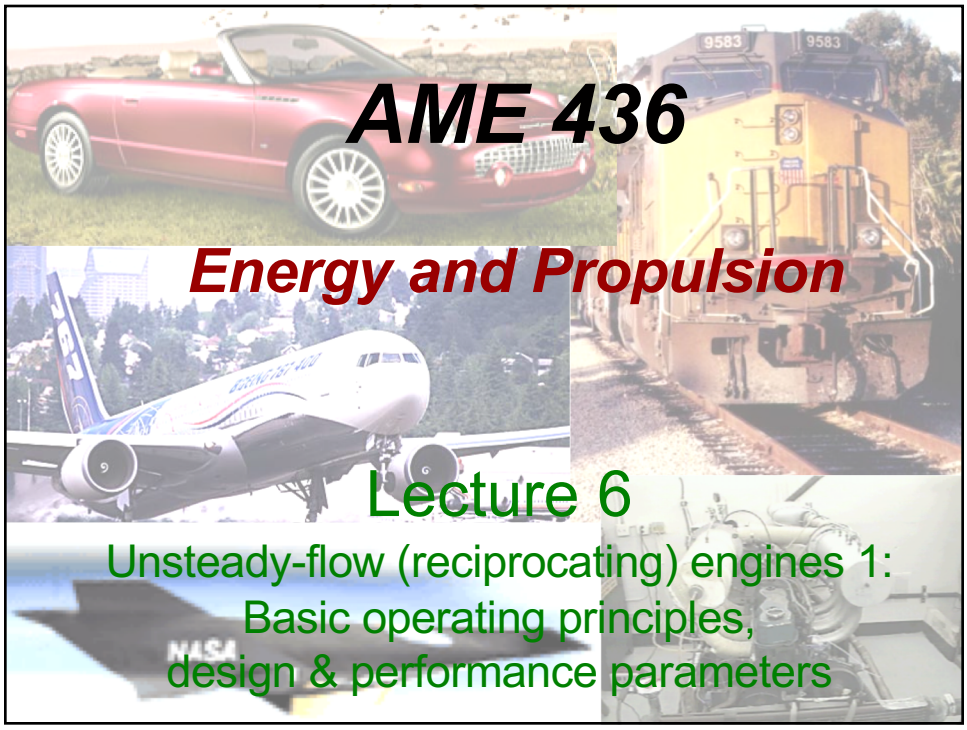

Outline

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- Classification of unsteady-flow engines
- Basic operating principles
  - Premixed-charge (gasoline) 4-stroke
  - Premixed-charge (gasoline) 2-stroke
  - Premixed-charge (gasoline) rotary or Wankel
  - Nonpremixed-charge (Diesel) 4-stroke
  - Nonpremixed-charge (Diesel) 2-stroke
- Design and performance parameters
  - Compression ratio, displacement, bore, stroke
  - Power, torque, work, Mean Effective Pressure
  - Thermal efficiency
  - Volumetric efficiency
  - Emissions

Classification of unsteady-flow engines

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- Most important distinction: premixed-charge vs. nonpremixed-charge
- Premixed-charge: frequently called "Otto cycle," "gasoline" or "spark ignition" engine but most important distinction is that the fuel and air are mixed before or during the compression process and a premixed flame is ignited (usually by spark)
- Nonpremixed-charge: frequently called "Diesel" or "compression ignition" but key point is that only air is compressed (not fuel-air mixture) & fuel is injected into combustion chamber after air is compressed
- Either premixed or nonpremixed-charge can be 2-stroke or 4-stroke, and can be piston/cylinder type or rotary (Wankel) type

Classification of unsteady-flow engines

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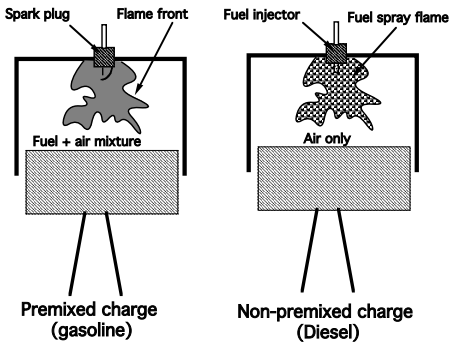
- Why is premixed-charge (typically gasoline) vs. nonpremixed-charge (typically Diesel) the most important distinction? Because it affects
  - Choice of fuels and ignition system
  - Choice of compression ratio (nonpremixed: higher, no knocking)
  - Tradeoff between maximum power (premixed) and efficiency (nonpremixed, higher compression)
  - Relative amounts of pollutant formation (premixed: generally lower NO_x & particulates; nonpremixed: lower CO & UHC)



4-stroke premixed-charge piston engine

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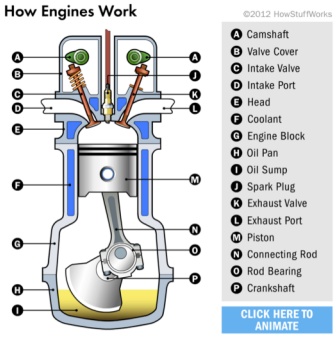
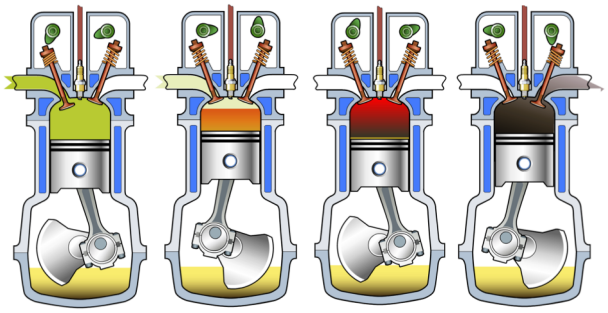
Animation: https://auto.howstuffworks.com/engine1.htm





Intake (piston moving down, intake valve open, exhaust valve closed)

Compression (piston moving up, both valves closed)

Expansion (piston moving down, both valves closed)

Exhaust (piston moving up, intake valve closed, exhaust valve open)

Ideally combustion occurs in zero time when piston is at the top of its travel between the compression and expansion strokes

2-stroke premixed-charge piston engine

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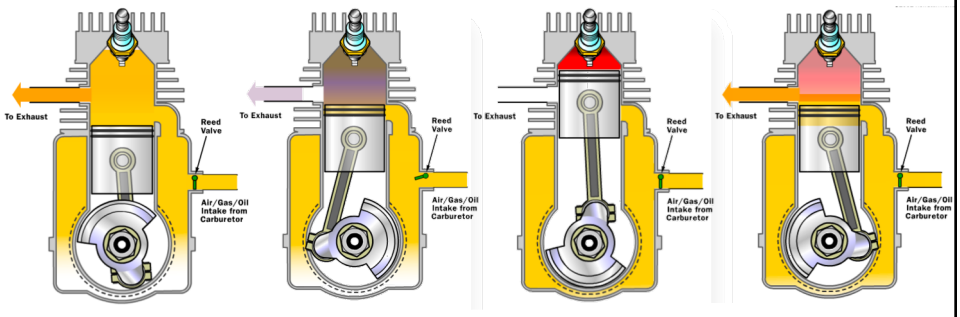
Animation: https://science.howstuffworks.com/transport/engines-equipment/two-stroke2.htm



Scavenging exhaust & filling comb. chamber (piston moving down, reed valve closed, intake & exhaust ports uncovered)

Filling crankcase (piston moving up, reed valve open, intake port closed, exhaust port open)

Expansion (piston moving down, both ports covered)

Exhaust & crankcase compression (piston moving down, intake port closed, exhaust port open)

2-stroke premixed-charge engine

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- Most designs have fuel-air mixture flowing first INTO CRANKCASE (?)
- Fuel-air mixture must contain lubricating oil
- 2-strokes gives ≈ 2x as much power since only 1 crankshaft revolution needed for 1 complete cycle (vs. 2 revolutions for 4-strokes)
- Since intake & exhaust ports are open at same time, some fuel-air mixture flows directly out exhaust & some exhaust gas gets mixed with fresh gas
- Since oil must be mixed with fuel, oil gets burned
- As a result of these factors, thermal efficiency is lower, emissions are higher, and performance is near-optimal for a narrower range of engine speeds compared to 4-stroke engines

Rotary or Wankel engine

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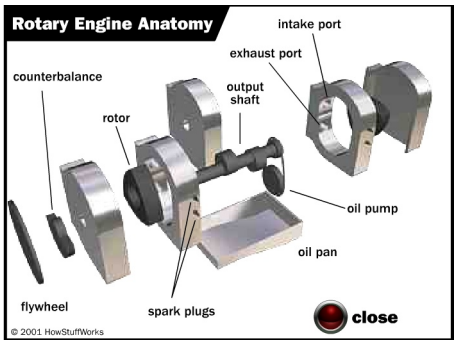
- Uses non-cylindrical combustion chamber
- One complete cycle per engine revolution without "short circuit" flow of 2-strokes
- Simpler, fewer moving parts, higher RPM possible
- Very fuel-flexible, e.g. can incorporate catalyst in combustion chamber since fresh gas is moved into chamber rather than being continually exposed to it (as in piston engine) – one engine could use gasoline, Diesel, methanol, etc.
- Difficult to seal BOTH vertices & flat sides of rotor! - seal longevity a problem too
- Large surface area to volume ratio means more heat losses



http://static.howstuffworks.com/flash/rotary-engine-exploded.swf

Rotary or Wankel engine

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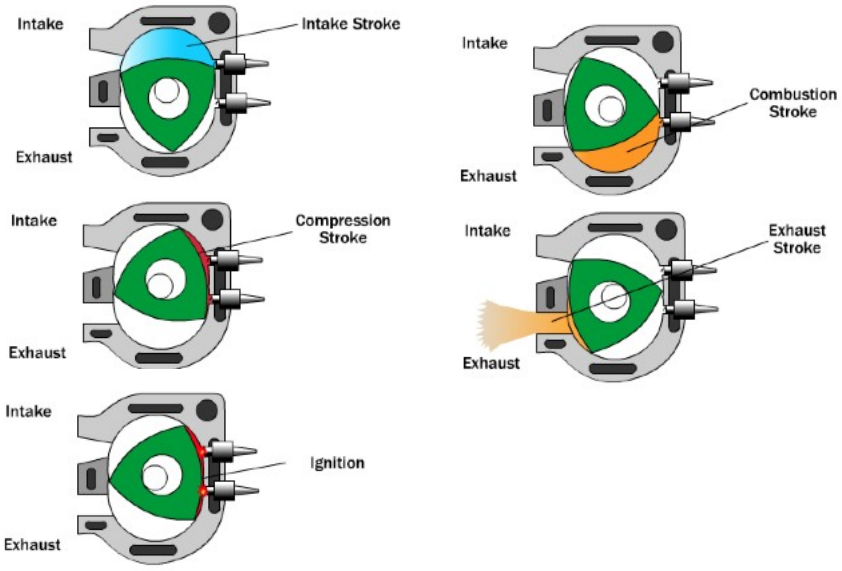

http://auto.howstuffworks.com/rotary-engine4.htm

4-stroke Diesel engine

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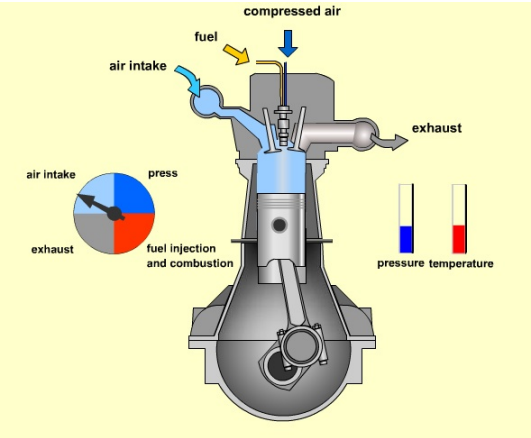
- Conceptually similar to 4-stroke gasoline, but only air is compressed (not fuel-air mixture) and fuel is injected into combustion chamber after air is compressed

http://auto.howstuffworks.com/diesel1.htm



2-stroke Diesel engine

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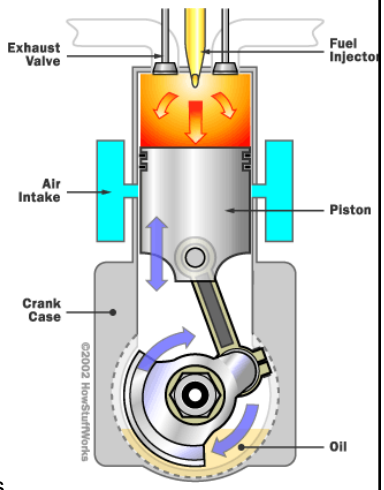
- Used in large engines, e.g. locomotives
- More differences between 2-stroke gasoline vs. diesel engines than 4-stroke gasoline vs. diesel
  - Air comes in directly through intake ports, not via crankcase
  - Must be turbocharged or supercharged to provide pressure to force air into cylinder
  - No oil mixed with air - crankcase has lubrication like 4-stroke
  - Exhaust valves rather than ports - not necessary to have intake & exhaust paths open at same time
  - Because only air, not fuel/air mixture enters through intake ports, "short circuit" of intake gas out to exhaust not a problem
  - Because of the previous 3 points, 2-stroke diesels have far fewer environmental problems than 2-stroke gasoline engines



auto.howstuffworks.com/diesel-two-stroke1.htm

Engine design & performance parameters

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- Compression ratio (r_c)

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

V_d = displacement volume = volume of cylinder swept by piston
V_c = clearance volume = volume of cylinder NOT swept by piston

- Bore (B) = cylinder diameter
- Stroke (L) = distance between maximum excursions of piston
- Displacement volume of 1 cylinder = $\pi B^2 L/4$; if B = L (typical), 5.7 liter, 8-cylinder engine, B = 9.7 cm
- Power = Angular speed (N) x Torque (τ) = $2\pi N\tau$

$$P \text{ (in horsepower)} \equiv \frac{N \text{ (revolutions per minute, RPM)} \times \tau \text{ (in foot pounds)}}{5252}$$

Classification of unsteady-flow engines

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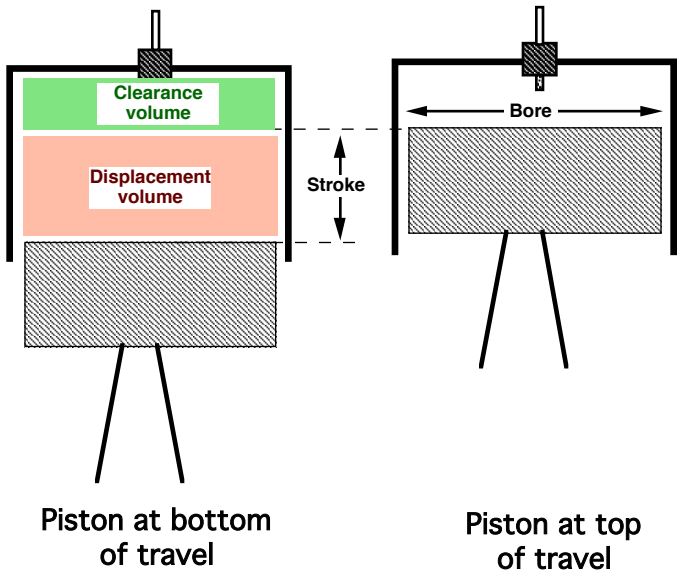

Engine design & performance parameters

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- Engine performance is specified in both in terms of power and engine torque - which is more important?
  - Wheel torque = engine torque x gear ratio tells you whether you can climb the hill
  - Gear ratio in transmission typically 3:1 or 4:1 in 1st gear, 1:1 in highest gear; gear ratio in differential typically 3:1
    - » Ratio of engine revolutions to wheel revolutions varies from 12:1 in lowest gear to 3:1 in highest gear
  - Power tells you how fast you can climb the hill
  - Torque can be increased by transmission (e.g. 2:1 gear ratio ideally multiplies torque by 2)
  - Power can't be increased by transmission; because of friction, power will decrease in transmission
  - Power tells you how fast you can accelerate or how fast you can climb a hill, but power to torque ratio ~ N tells you what gear ratios you'll need to do the job

Engine design & performance parameters

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- Indicated work - work done for one cycle as determined by the cylinder P-V diagram = work acting on piston face
- Net indicated work = $W_{i,net} = \int PdV$ over whole cycle = net area inside P-V diagram
- Indicated work consists of 2 parts
  - Gross indicated work $W_{i,gross}$ - work done during power cycle
  - Pumping work $W_{i,p}$ - work done during intake/exhaust pumping cycle
- $W_{i.net} = W_{i,gross} - W_{i,pump}$
- Indicated power = $W_{i,x}N/n$, where x could be net, gross or pumping and n = 2 for 4-stroke engine, n = 1 for 2 stroke engine (4-stroke needs 2 engine revs for a complete cycle, 2-stroke only 1 rev)
- Brake work (W_b) or brake power (P_b) = work or power at the shaft coming out of the engine
- What's the difference between brake & indicated work? FRICTION

$W_{i,g} = W_b + W_f + W_{i,p}$; W_f = friction work

W_f also includes work to drive cooling fan, water & oil pumps, generator, air conditioner, …

Engine design & performance parameters

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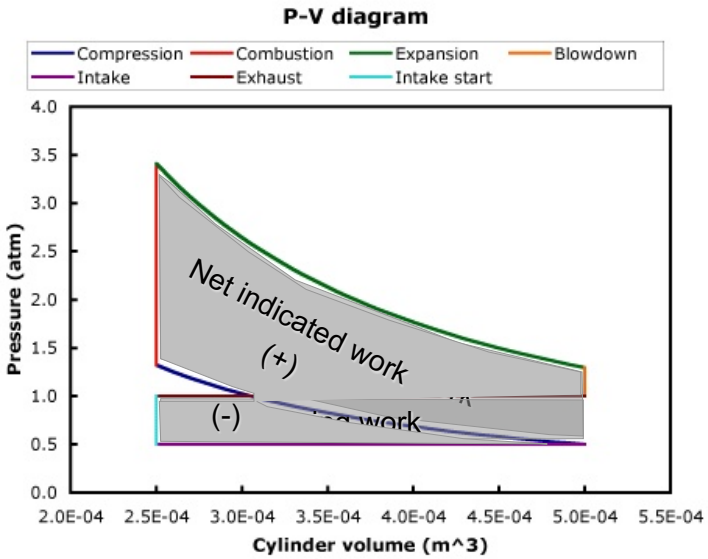
Animation: gross & net indicated work, pumping work



Real engine P-V diagram

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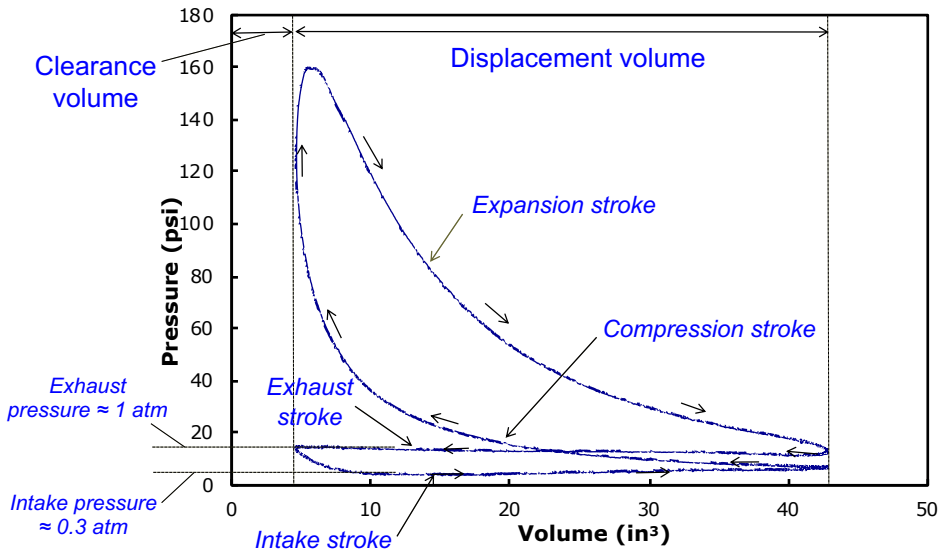

Indicated vs. brake work or power

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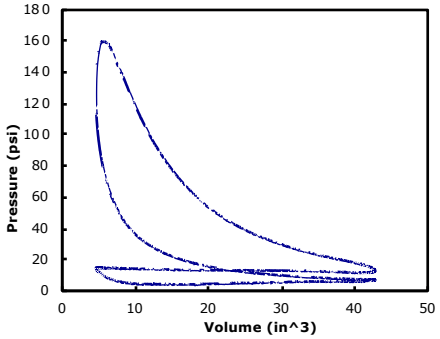
- Indicated
  - Measure cylinder P vs. time
  - Measure crank angle vs. time
  - Translate crank angle to volume (V) with engine geometry (piston / crankshaft / connecting rod)
  - Plot P vs. V
  - $\int PdV$ = indicated work (W_{ind})
  - Power = $W_{ind}N/n$
- Brake
  - Connect engine to dynamometer (e.g., electrical generator) to simulate load that vehicle puts on engine
  - Measure torque required to spin generator at a particular speed (N)
  - Power = Torque x N / 5252

  (when Power in hp, Torque in ft lbf and N in rev/min)



Engine design & performance parameters

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- Mechanical efficiency - measure of importance of friction loss = (brake work or power) / (indicated work or power)
- Thermal efficiency (η_{th}) = (what you get / what you pay for) = (power ouput) / (fuel heating value input)

$$\eta_{th} \equiv \frac{\text{Power output (brake or indicated)}}{\dot{m}_{\text{fuel}} Q_R}$$

- Specific fuel consumption (i = indicated, b = brake)

$$isfc \equiv \frac{\dot{m}_{\text{fuel}}}{\text{indicated power}}; bsfc \equiv \frac{\dot{m}_{\text{fuel}}}{\text{brake power}}$$

units usually pounds of fuel per horsepower-hour (yuk!)

- Combining the above definitions

$$\eta_{th,i} \equiv \frac{1}{(\text{isfc}) Q_R}; \eta_{th,b} \equiv \frac{1}{(\text{bsfc}) Q_R}$$

Engine design & performance parameters

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- Volumetric efficiency (η_v) = (mass of air actually drawn into cylinder) / (mass of air that ideally could be drawn into cylinder)

$$\eta_v \equiv \frac{\dot{m}_{\text{air}} \text{ (measured)}}{\rho_{air} V_d N / n}$$

where ρ_{air} is at ambient conditions = $P_{ambient}/RT_{ambient}$

- Volumetric efficiency indicates how well the engine "breathes" - what lowers η_v below 100%?
  - Throttling (intentional pressure drop with a valve to reduce air mass flow, thus power)
  - (Undesired) pressure drops in intake manifold & intake valves
  - (Undesired) temperature rise due to heating of air in intake system
  - Volume occupied by fuel
  - Non-ideal valve timing
  - "Choking" (air flow reaching speed of sound) in part of intake system having smallest area (passing intake valves)
- Will be > 100% with turbocharging or supercharging
- See Heywood (2nd ed., p. 228) for good summary of these effects

Engine design & performance parameters

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- Mean effective pressure (MEP)

$$MEP \equiv \frac{\text{Work per cycle}}{\text{Displacement volume}} = \frac{\oint P\,dV}{V_d} = \frac{(Power)n/N}{V_d} = \frac{(Power)n}{V_d N}$$

- Power could be brake, indicated, friction or pumping power, leading to BMEP, IMEP, FMEP, PMEP
- Note Power = Torque x 2πN, thus

$$Torque \equiv \frac{(MEP)(V_d)}{2\pi n}$$

- MEP is useful for 2 reasons
  - Since it's proportional to power or work, we can add and subtract pressures just like power or work
  - (More important) it normalizes out the effects of engine size (V_d), speed (N) and 2-stroke vs. 4-stroke (n) – parameter for comparing different engines and operating conditions
- Typical 4-stroke engine, IMEP ≈ 120 lb/in^2 ≈ 10 atm - how to get more? Turbocharge - increase P_{intake} above 1 atm, more fuel & air stuffed into cylinder, more heat release, more power

Engine design & performance parameters

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- MEP is useful for 2 reasons
  - Since it's proportional to power or work, we can add and subtract pressures just like power or work
  - (More important) it normalizes out the effects of engine size (V_d), speed (N) and 2-stroke vs. 4-stroke (n) – parameter for comparing different engines and operating conditions
- Typical 4-stroke engine, IMEP ≈ 150 lb/in^2 ≈ 10 atm - how to get more? Turbocharge - increase P_{intake} above 1 atm, more fuel & air stuffed into cylinder, more heat release, more power

Engine design & performance parameters

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- Pumping power = (pumping work)(N)/n = (ΔP)(ΔV)(N)/n
  = $(P_{exhaust} - P_{intake})V_dN/n$
  but PMEP = (pumping power)n/(V_dN), thus PMEP = $(P_{exhaust} - P_{intake})$
  (wasn't that easy?) (this assumes "pumping loop" is a rectangle)
- Estimate of IMEP

$$IMEP_g \equiv \frac{\text{(Gross indicated power) n}}{V_d N} = \frac{(\eta_{th,i,g}\dot{m}_{fuel}Q_R)n}{V_d N}$$

$$= \frac{(\eta_{th,i,g}\dot{m}_{air}[f/(1-f)]Q_R)n}{V_d N} = \frac{\eta_{th,i,g}(\eta_v \rho_{air,ambient} V_d N/n)Q_R n}{V_d N}\frac{f}{1-f}$$

$$= \eta_{th,i,g}\eta_v Q_R\left(\frac{P_{\text{ambient}}}{RT_{\text{ambient}}}(1-f)\right)\frac{f}{1-f} \Rightarrow \boxed{\frac{IMEP_g}{P_{ambient}} = \frac{\eta_{th,i,g}\eta_v f Q_R}{RT_{\text{ambient}}}}$$

- Typical engine at wide-open throttle ($P_{intake} = P_{ambient}$):
  $\eta_{th,i,g} \approx 35\%$, $\eta_v \approx 90\%$, $f \approx 0.0641$ (at stoichiometric),
  $Q_R = 4.3 \times 10^7$ J/kg, R = 287 J/kgK, $T_{intake} = 300$K
  $\Rightarrow IMEP_g / P_{intake} \approx 10.1$

Example #1

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Estimate the brake power of a 5.7 liter (= 0.0057 m^3) 4-stroke (n = 2) engine at 6000 RPM with brake thermal efficiency $\eta_{th,b} = 30\% = 0.30$ and volumetric efficiency $\eta_v = 90\% = 0.90$ using a stoichiometric gasoline-air mixture ($f_{stoich} = 0.0641$, $Q_R = 4.3 \times 10^7$ J/kg)

$$\dot{m}_{air} = \eta_v \rho_{air} V_d N/n = (0.90)\frac{1.18kg}{m^3}(0.0057m^3)\frac{6000}{\text{min}}\frac{\text{min}}{60\text{sec}}\frac{1}{2} = \frac{0.303kg}{\text{sec}}$$

$$Power = \eta_{th}\dot{m}_{fuel}Q_R = \eta_{th}\dot{m}_{air}(FAR)Q_R = \eta_{th}\frac{\dot{m}_{air}f}{1-f}Q_R$$

$$= (0.30)\frac{\frac{0.303kg}{\text{sec}}0.0641}{1-0.0641}\frac{4.3\times10^7 J}{kg} = 2.68\times10^5 W\frac{hp}{746W} = 358hp$$

Example #2

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In a laboratory test of a 4-stroke engine with V_d = 3.05 liters at N = 3000 RPM the following data were measured: net IMEP 107.9 lbf/in^2, 70.32 brake horsepower, fuel flow rate 16.66 kg/hr, air flow rate 269.6 kg/hr. The fuel is C_8H_{18} (Q_R = 4.3 x 10^7 J/kg.) The ambient air temperature is 295K. The intake pressure gauge is broken, so the intake pressure is not known. Determine:

a) BMEP

$$BMEP = \frac{(BrakePower)n}{V_d N} = \frac{(70.32hp)(2)(746Watt/hp)}{3.05liter(m^3/1000liter)(3000/\min)(\min/60\sec)}$$

$$= 6.88 \times 10^5 N/m^2 = 6.79atm$$

b) Friction MEP

FMEP = IMEP – BMEP

IMEP = (107.9 lb/in^2)(4.448N/lb)(in/0.0254m)^2 = 7.44 x 10^5 N/m^2

FMEP = 7.44 x 10^5 N/m^2 – 6.88 x 10^5 N/m^2 = 5.6 x 10^4 N/m^2 = 0.55 atm

c) Equivalence ratio

$C_8H_{18} + 12.5(O_2 + 3.77N_2) \rightarrow 8\ CO_2 + 9\ H_2O + 12.5(3.77)\ N_2$

Stoichiometric fuel/air: (8(12)+18(1))/[12.5((32)+3.77(28))] = 0.0663

Actual fuel/air: (16.66 kg/hr)/(269.6 kg/hr) = 0.06179

Equivalence ratio = 0.06179/0.0663 = 0.932

Example #2 (continued)

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d) Brake thermal efficiency

$$\eta_{brake} = \frac{BrakePower}{\dot{m}_{fuel} Q_R} = \frac{(70.32hp)(746Watt/hp)}{(16.66kg/hr)(hr/3600\sec)(4.3 \times 10^7 J/kg)} = 0.264$$

e) Indicated torque

$$\text{Indicated torque} = (IMEP)(V_d)/2\pi n$$

$$= \frac{(107.9lbf/in^2)(4.448N/lbf)(in/0.0254m)^2(3.05liters)(m^3/10^3 liters)}{2\pi(2)}$$

$$= 180.6\ Nm(lbf/4.448N)(3.281ft/m) = 133.2\ ft\ lbf$$

f) Is this engine throttled, turbocharged or neither? Explain. (Hint: compute the volumetric efficiency.)

$$\eta_v \equiv \frac{\dot{m}_{air}\ (\text{measured})}{\rho_{air} V_d N/n} = \frac{(269.6kg/hr)(hr/3600\sec)}{(1.18kg/m^3)(3.05liter)(m^3/1000liter)(3000/\min)(\min/60\sec)/2}$$

$$= 0.832 < 1 \Rightarrow throttled$$

Summary

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- Many mechanical implementations of unsteady-flow engines exist, but all are based on a thermodynamic cycle consisting of compression, combustion, expansion
- The factor that affects engine design and performance more than any other is whether the engine is premixed-charge or nonpremixed-charge
- Because of different fueling & exhaust scavenging methods, each type of engine (premixed vs. nonpremixed-charge, 2-stroke vs 4-stroke) is optimal for a different application
- Many measures of engine performance are employed - be careful!
  - Work and power – indicated (gross or net) vs. brake
  - Efficiencies - thermal vs. volumetric
  - Mean Effective Pressure - brake, indicated, pumping, friction