8.21 The Physics of Energy
Fall 2009

8.21 Lecture 11

Internal Combustion Engines

October 2, 2009

Internal Combustion Engines

Much energy used for transport–cars, trucks, planes, boats, . . .

- U.S.: 25% Energy use, 33% CO_2
- Globally 15%/20%, growing

Presents unique challenge: need portable fuel, light engine

Engine type	Use	Cycle
Spark ignition	cars, light trucks	Otto (Const. V)
Compression ignition	trucks, heavy vehicles	Diesel (Const. P)
Gas turbines	airplanes	Brayton

Most cars $\sim$ 20%-25% efficient.

Increase 5%: save 15 EJ/year globally! (200M people's total E use)

4-stroke Spark Ignition (SI) engine: stages of operation

4-stroke SI engine image removed due to copyright restrictions.

[Milton]

(a) Air/fuel intake: piston goes down

(b) Compression: piston goes up

(c + d) Power: ignition, combustion, piston goes down

(e) Exhaust: piston goes up

Reciprocating SI engine

Reciprocating SI engine image removed due to copyright restrictions.

- First IC engines modeled on cannon!
- Reciprocating engine: linear piston motion
- Connecting rod $\rightarrow$ rotates crankshaft
- Crankshaft $\rightarrow$ camshaft $\rightarrow$ valve control
- Piston up: top dead center (TDC/TC)
- Single cycle: crankshaft rotates twice
- Max/min volume: $V_1/V_2 \quad (V_t/V_c)$
  Displaced volume $V_1 - V_2$ $(V_t - V_c = V_d)$
- Compression Ratio $r = V_1 : V_2$ (typical 9.5:1)

[Heywood]

Idealize as thermodynamic Otto cycle (constant volume combustion)

Otto cycle images removed due to copyright restrictions.

[Milton]

Otto + intake/exhaust [Milton]

$1 \longrightarrow 2$. Adiabatic compression: good approx. for compression (b)

$2 \longrightarrow 3$. Isometric heating: OK approximation for combustion (c)

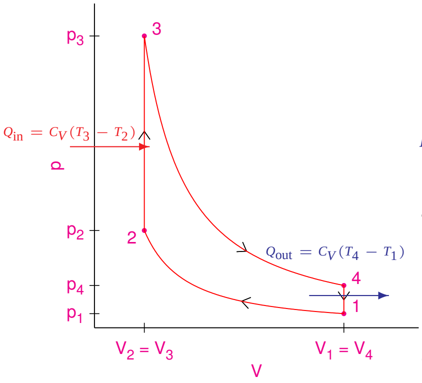
$3 \longrightarrow 4$. Adiabatic expansion: OK approximation for power stroke (d)

$4 \longrightarrow 1$. Isometric cooling: OK approx. for exhaust + intake (e + a)

Isometric cooling really just “blowdown”;

Better: intake + exhaust as separate constant p (*isobaric*) processes

"Ideal gas" Otto cycle analysis



- Approximate combustion at constant volume
- Q_{in} from combustion of fuel

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$p_1 V_1^\gamma = p_2 V_2^\gamma \Rightarrow T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

$$\Rightarrow T_2 = T_1 r^{\gamma-1} \quad (r = V_1/V_2)$$

and similarly $T_3 = T_4 r^{\gamma-1}$

So

$$\eta = 1 - \frac{1}{r^{\gamma-1}} = \frac{T_2 - T_1}{T_2}$$

Critical feature: Compression ratio r

Hydrocarbons: molecules composed of hydrogen + carbon atoms

- Crude oil: mix of many hydrocarbons
- Refineries: separate by properties
- Gasoline: $\sim$ 500 molecules, 5-12 C's

Mixed for: High compression/efficiency,
Minimize pollution

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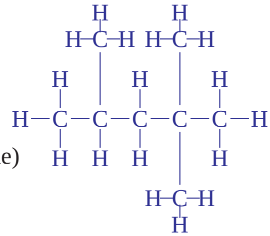
[Heywood]

iso-octane
(2-2-4-trimethylpentane)



Combustion

SI: Spark Ignites fuel-air mixture, HC's + $O_2 \rightarrow H_2O + CO_2$

e.g. iso-octane: $2\ C_8H_{18} + 25\ O_2 \longrightarrow 18\ H_2O + 16\ CO_2 + 10.94$ MJ

where $\Delta H^{\text{combustion}}_{\text{iso-octane}} \cong 5.47\ \text{MJ/mol} \cong 47.9\ \text{MJ/kg (hhc)}$

Air/fuel ratio nomenclature:

Stoichiometric: just enough O_2 to burn all fuel (gasoline: $\cong 14.7 : 1$)

Lean: excess oxygen (higher efficiency)

Rich: excess fuel (lower efficiency, slightly rich $\rightarrow$ slight power increase)

Exhaust: CO_2, H_2O + unburned HC's, CO, NO_x, . . .

Combustion process + “knock”

Image removed due to copyright restrictions.

[Milton]

Image removed due to copyright restrictions.

[Heywood]

- Combustion process: $\sim 1/6$ rotation centered into expansion phase
- Heat + pressure $\Rightarrow$ premature combustion: Knock
- Straight paraffins knock most easily
  Measured by “critical compression ratio”,
  $\text{CCR}_{iso-octane} \sim 2-3\times\ \text{CCR}_{n-heptane}$
- “Octane rating” N: Knocks as $N\%$ iso-octane, $100 - N\%$ n-heptane
- 93 octane gasoline: knocks $r \sim 10.5$
- Additives: aromatics, lead,…improve
- Bottom line: $r_{\text{max}} \approx 10$
  with current gasoline mixtures

Real SI engines

Maximum compression ratio: 10:1

At 1500-2500 K,
$\gamma_{\text{hot air}} \approx \gamma_{\text{air+spent fuel}} \approx 1.3$

$$\eta_{\text{Otto}} = \frac{1}{1 - r^{\gamma-1}} \cong 0.50$$

Theoretical "Ideal gas" thermo analysis: 50% efficiency

Real SI engines: max 35-40%. *e.g.* 4-cylinder Camry: $\eta_{\text{max}} \approx 35\%$

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SI engine losses

- Combustion not instantaneous
- Heat loss during expansion
- Blowdown: not constant volume
- Exhaust/intake: "pumping losses"

Throttle: reduces efficiency

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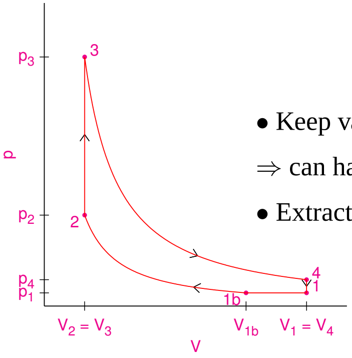
- Let up on gas: throttle reduces air/fuel flow (typical driving: intake 0.5 Atm)

$\Rightarrow$ reduced pressure on intake (increased pumping loss)

Combining all these inefficiencies, power to systems:

$\sim 25\%$ delivered mechanical energy, as in transport example

Atkinson cycle

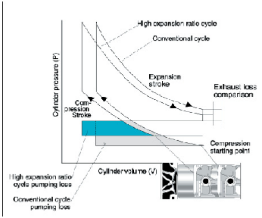


- Keep valve open at start of compression

⇒ can have exp. ratio > comp. ratio

- Extract more energy w/ expansion

- Reduces pumping losses

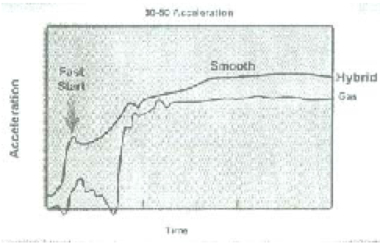


[DOE report]

Atkinson cycle in real engines

Used in 2007 Toyota Camry hybrid

- Expansion ratio 12.5:1 (compression ratio 9.5:1)
- Maximum efficiency 35% → 38% [DOE report]
- Reduces pumping losses
- Maximum power 160hp → 147hp, made up by battery assist
- Superior acceleration



[DOE report]

Diesel (constant pressure combustion) cycle — Compression Ignition (CI)

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- Inject fuel after compression

$\Rightarrow$ can have $r = V_1/V_2 \sim 15 - 20 : 1$

- Efficiency $\rightarrow$ 70% theoretical, $\sim$ 45% realized (ideal cycle inaccurate)
- Need heavy piston/cylinder head $\Rightarrow$ trucks, buses, boats, ...
- More flexible fuel options ($\sim$ *biodiesel*)

SUMMARY

- SI engines modeled by "ideal gas" Otto (constant V combustion) cycle
- $\eta_{\text{Otto}} = \frac{1}{1-r^{\gamma-1}}$
- $r = V_1/V_2$ limited to ~ 10 by "knock"
- Real engines: combustion process, heat loss, pumping reduce $\eta \to\sim 35\%$ max, 25% average delivered.
- Atkinson cycle: valve timing $\to$ more expansion, efficiency
- Diesel (constant P combustion): CI $\to$ increased compression, efficiency