SAND2019-2935PE

Co-Optimization of Fuels & Engines

Comparison of Combustion Modes

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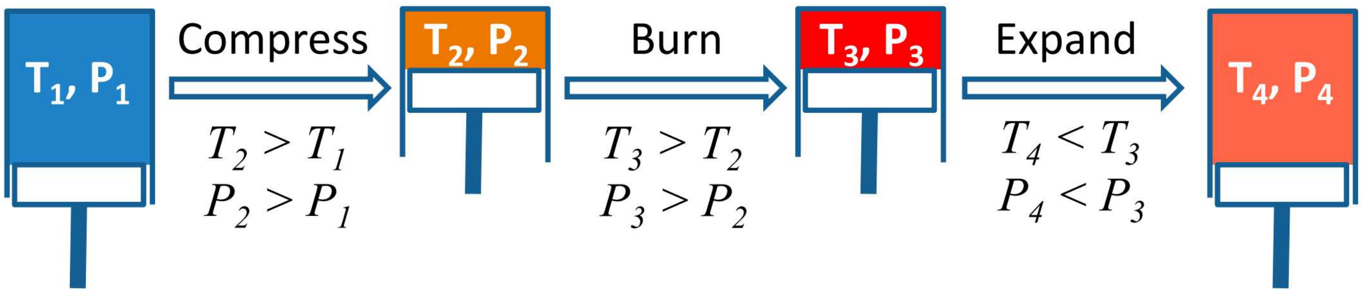
March 13, 2019

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

This research was sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE). Optical engine experiments were conducted at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

A simplified temperature perspective on engine efficiency: Efficiency depends on compression-temperature multiple (M)



For the gas, temperature “is” (internal) energy: $E \sim T$

Compression multiplies temperature: $T_2 = M \cdot T_1$

Burning fuel adds temperature: $T_3 = T_2 + A$

Expansion divides temperature: $T_4 = T_3 / M$

Left-over energy in gas is change in temperature: $\Delta E = T_4 - T_1$

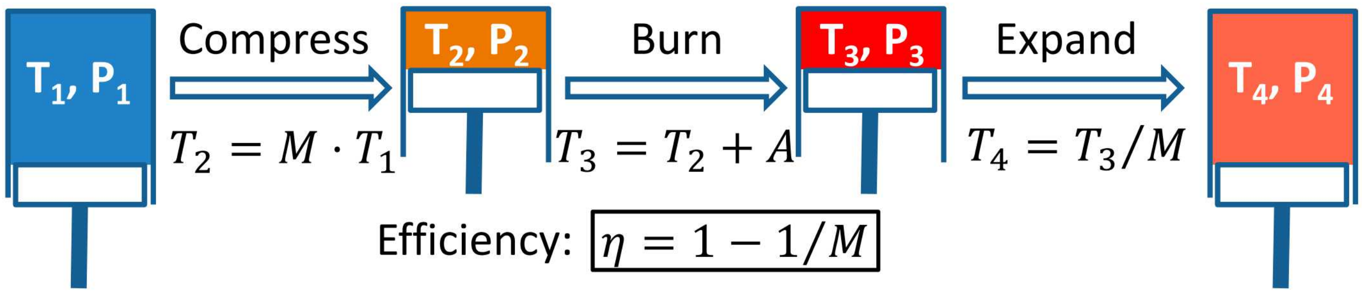
Efficiency is fraction of fuel energy not left over: $\eta = (A - \Delta E)/A$

Do some algebra to simplify for efficiency: $\boxed{\eta = 1 - 1/M}$

Some stuff we’re ignoring:

- Heat transfer losses
- Combustion phasing
- Variable gas properties
- Incomplete combustion
- Friction losses
- Pumping losses
- Valve timing

A kinetic-theory-of-gases perspective on engine efficiency: Small molecules compress to higher T for high efficiency (γ)



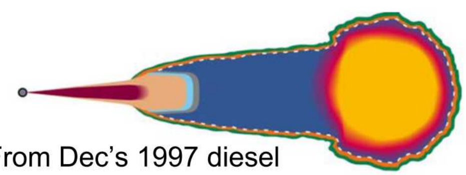
How do we make M big to get higher compressed temperature and thus higher efficiency?

1. Compress more: smaller compressed volume (V_2) relative to V_1
   i.e., increase compression ratio $R_C = V_1 / V_2$
2. Use a gas that gets hotter when compressed (more energy goes into velocity of molecules)
   i.e., use a gas with a low molar heat capacity (C_V), i.e., a high specific heat ratio (γ)
   mono-atomics (e.g., He, Ne, Ar): γ = 1.67 (energy in translation only)
   di-atomics (e.g., O_2, N_2): γ = 1.4 (translation + rotation, + vibration at high T)
   tri-atomics (e.g., H_2O, CO_2): $\gamma \cong$ 1.3 (more rotation and/or vibration)
   vaporized liquid fuels: $1.0 < \gamma < 1.3$ (many vibrational degrees of freedom)

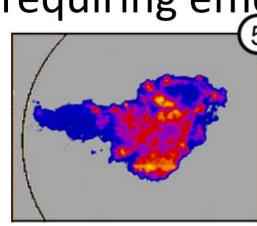
Mixing-(diffusion flame)-Controlled Compression Ignition: High efficiency due to high R_C & γ; PM & NOx challenges

Combustion rate depends on how fast spray- and flow-generated turbulence mixes gases in the fuel zone and gases in the air zone into a diffusion flame at the interface between the two zones.

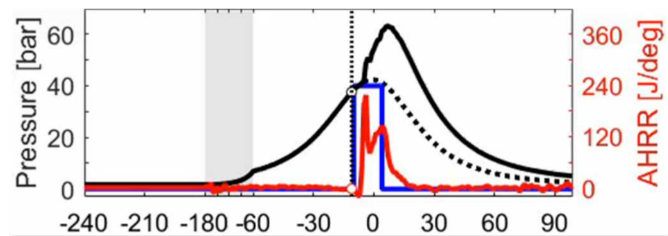
- ✓ Gas during compression is air + EGR, so γ is high
- ✓ Overall fuel-lean, so γ stays high after combustion
- ✓ No premixed fuel+air to knock, so R_C is high
- ✘ Emissions of particulate matter (PM) and nitrogen oxides (NOx) are high, requiring efficiency tradeoffs



From Dec's 1997 diesel conceptual model (SAE 970873)



LII: Soot Concentration
Shortly after the premixed fuel burns, soot is formed in the hot, fuel-rich region throughout the jet cross-section.



Some R&D: Low-sooting fuels, esp. at high EGR; leaner lifted flame; ducted fuel injection (DFI); multi-mode with ACI

Spark Ignition (premixed-flame-controlled) Combustion: Lower efficiency due to lower R_C & γ; knocking challenge

Combustion rate depends on how fast flow-generated turbulence mixes heat and mass from the burned zone into the unburned zone through a premixed flame at the interface between the two zones.

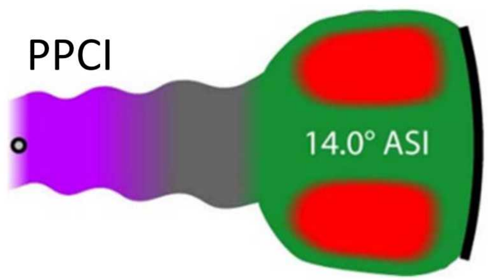
- ✘ Fuel+air+EGR during compression: low γ
- ✘ Stoichiometric, so low γ after combustion
- ✘ Knock in unburned gas zone limits R_C
  - especially with boost (& gasoline)
- ✓ Three-way catalyst: low NOx, CO, and UHC

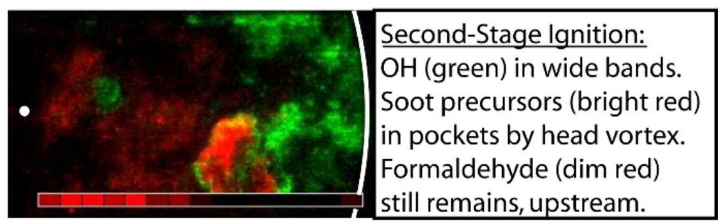
Some R&D: Autoignition-resistant (e.g., high octane number) fuels; EGR-tolerant fuels/engines; fuel-lean flame propagation (precludes 3-way catalyst), multi-mode with ACI

Advanced (kinetically controlled) Compression Ignition : High η due to R_C & γ; ignition/noise, CO, UHC challenges

Ignition and combustion rate depend on how local T, P, ϕ, fuel molecular structure, and/or spray- and/or flow-generated turbulence affect chemical-kinetic reaction rates

- ✓ Lean fuel + air + EGR during compression: medium γ
- ✓ Overall fuel-lean, so γ stays high after combustion
- ✓ Dilute mixtures tolerate more compression: medium R_C
- ✗ Difficult to control combustion rate; incomplete combustion





From LTC conceptual model (PECS 39:215-284, 2013)

Some R&D: Fuel property and mixture preparation effects on ignition and combustion rate; in-cylinder CO & UHC mitigation