SI engine combustion I

SI – engine combustion:
How to “burn” things?
Reactants $\rightarrow$ Products

Premixed
- Homogeneous reaction
  - Not limited by transport process
  - Fast/slow reactions compared with other time scale of interest
- Premixed flame
  - Examples: gas grill, SI engine combustion

Detonation
- Pressure wave driven reaction

Non-premixed
- Diffusion flame
  - Examples: candle, diesel engine combustion
SI ENGINE COMBUSTION

- Premixed flame
  - Laminar flame speed

- Turbulent enhancement of combustion
  - Wrinkled laminar flame

LAMINAR FLAME SPEEDS

Fig. 9-25 Laminar burning velocity of several fuels as function of equivalence ratio, at 1 atm and 300 K.

Fig. 9-26 Effect of burned gas mole fraction in unburned mixture on laminar burning velocity. Fuel: gasoline.
(Note that actual burned gas from non-stoichiometric combustion would render the charge $\Phi$ different from the metered $\Phi$).
Schematic of SI engine flame propagation

Fig. 9-4 Schematic of flame propagation in SI engine: unburned gas (U) to left of flame, burned gas to right. A denotes adiabatic burned-gas core, BL denotes thermal boundary layer in burned gas.

Typical pressure and mass fraction burned ($x_b$) curves

SI engine; 1500 rpm, 0.38 bar intake pressure

Useful conversions:
- 1000 rpm: 6°CA/ms
- 1200 rpm: 20 Hz
  (For 4 stroke engine 10 cycle/s 100 ms/cycle)
Combustion produced pressure rise

1. Pressure is uniform, changing with time
2. For mass $\delta m$: $h_b = h_u$ (because $m$ is allowed to expand against prevailing pressure)
3. $T$ rise is a function of fuel heating value and mixture composition
   - e.g. at $\phi = 1, T_u \sim 700$ K, $T_b \sim 2800$ K
4. Hence burned gas expands: $p_b \sim \frac{1}{4} p_u$; $\delta V_b \sim 4 \delta V_u$

5. Since total volume is constrained. The pressure must rise by $\delta p$, and all the gas in the cylinder is compressed.
6. Both the unburned gas ahead of flame and burned gas behind the flame move away from the flame front
7. Both the unburned gas and burned gas temperatures rise due to the compression by the newly burned gas
8. Unburned gas state: since heat transfer is relatively small, the temperature is related to pressure by isentropic relationship
   - $T/T_u = (p/p_u)^{\gamma_u}/\gamma_u$
9. Burned gas state:
Burn duration

- Burn duration as CA-deg.: measure of burn progress in cycle
- For modern fast-burn engines under medium speed, part load condition:
  - $\Delta \theta_{0-10\%} \sim 15^\circ$
  - $\Delta \theta_{0-50\%} \sim 25^\circ$
  - $\Delta \theta_{0-90\%} \sim 35^\circ$
- As engine speed increases, burn duration as CA-deg.:
  - Increases because there is less time per CA-deg.
  - Decreases because combustion is faster due to higher turbulence
    - Net effect: increases approximately as $\propto \text{rpm}^{0.2}$
Optimum Combustion Phasing

- Heat release schedule has to phase correctly with piston motion for optimal work extraction
- In SI engines, combustion phasing controlled by spark
  - Spark too late
    - Heat release occurs far into expansion and work cannot be fully extracted
  - Spark too early
    - Effectively "lowers" compression ratio
    - Increased heat transfer losses
    - Also likely to cause knock
- Optimal: Maximum Brake Torque (MBT) timing
  - MBT spark timing depends on speed, load, EGR, φ, temperature, charge motion, ...
  - Torque curve relatively flat: roughly 5 to 7°CA retard from MBT results in 1% loss in torque

Spark timing effects

Fig. 9-3 (a) Cylinder pressure versus crank angle for overadvanced spark timing (50° BTDC), MBT timing (30° BTDC), and retarded timing (10° BTDC). (b) Effect of spark advance on brake torque at constant speed and A/F, at WOT
Control of spark timing

Obtaining combustion information from engine cylinder pressure data

1. Cylinder pressure affected by:
   a) Cylinder volume change
   b) Fuel chemical energy release by combustion
   c) Heat transfer to chamber walls
   d) Crevice effects
   e) Gas leakage

2. Obtaining accurate combustion rate information requires
   a) Accurate pressure data (and crank angle indexing)
   b) Models for phenomena a,c,d,e, above
   c) Model for thermodynamic properties of cylinder contents

3. Available methods
   a) Empirical methods (e.g. Rassweiler and Withrow SAE 800131)
   b) Single-zone heat release or burn-rate model
   c) Two-zone (burned/unburned) combustion model
Typical piezoelectric pressure transducer spec.

**Technical Data**

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<td>Plug, ceramic insulator Type</td>
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Kistler 6125

**Sensitivity of NIMEP to crank angle phase error**

SI engine; 1500 rpm, 0.38 bar intake pressure

![Graph showing sensitivity of NIMEP to crank angle phase error](image)
Cylinder pressure

Fig. 9-10  (a) Pressure-volume diagram; (b) log p-log(V/V\text{max}) plot; 1500 rpm, MBT timing, IMEP = 5.1 bar, Φ = 0.8, \( r_c = 8.7 \), propane fuel.

Burned mass analysis –
Rassweiler and Winthrow
(SAE 800131)

- Advantage: simple
  - Need only \( p(\theta) \), \( p_0 \), \( p_f \), and \( n \)
  - \( x_b \) always between 0 and 1
During combustion \( V = V_u + V_b \)
Unburned gas volume, back tracked to spark (0)
\( V_{u,0} = V_u(p/p_0)^{1/n} \)
Burned gas volume, forward tracked to end of combustion (f)
\( V_{b,f} = V_b(p/p_f)^{1/n} \)
Mass fraction burned
\( x_b = 1 - \frac{V_{u,0}}{V_0} = \frac{V_{b,f}}{V_f} \)
Hence, after some algebra
\( x_b = \frac{p^{1/n}V - p_0^{1/n}V_0}{p_f^{1/n}V_f - p_0^{1/n}V_0} \)

(There are two procedures described in the paper; this is one of them)
Heat release analysis

Fig. 9-11 Open system boundary for heat-release analysis

Energy balance:

\[
\frac{dQ_{ch}}{dt} = \frac{dU_s}{dt} + pdV/dt + \frac{dQ_{ht}}{dt} + \frac{h'}{dm_c}/dt - \frac{h_{inj}}}{dm_f}/dt
\]

Fuel chemical energy release

\[
\frac{dQ_{ch}}{dt} = \frac{dU_s}{dt} + pdV/dt + \frac{dQ_{ht}}{dt} + \frac{h'}{dm_c}/dt - \frac{h_{inj}}}{dm_f}/dt
\]

Sensible energy change

Work transfer

Heat loss to walls

Flow into crevice

Injected enthalpy

Net heat released

Results of heat-release analysis

Fig. 9-12 Results of heat-release analysis showing the combustion inefficiency and the corrections due to heat transfer and crevice effect.

A Color Schieren Movie taken in a Special Visualization Engine

- Square piston engine
- Visualization by color-schlieren method
  - Captures density gradients
- Note:
  - Flame propagation process
  - Outgasing from crevices

Square piston flow visualization engine

- Bore: 82.6 mm
- Stroke: 114.3 mm
- Compression ratio: 5.8
- Operating condition:
  - Speed: 1400 rpm
  - \( \Phi \): 0.9
  - Fuel: propane
  - Intake pressure: 0.5 bar
  - Spark timing: MBT
Flame Propagation (Fig 9-14)

1400 rpm
0.5 bar inlet pressure

Cylinder pressure, atm

Spark

Fraction burned

Crank angle, deg