4A13 Examples

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1 Overview

– **SI engines** :

- Valve timings and volumetric efficiency.
- Residual gas recirculation.
- Intake and fuel injection systems (port fuel vs. direct injection).
- Compression limits (autoignition, knock, superknock).
- Flame propagation, heat release rate.
- Spark timing (early vs. late ignition).
- Effect of speed and throttling on mep.
- Torque-speed diagrams (with vs. without turbocharging, downsizing).

2 Questions

1. **Why is throttle required in gasoline engines?**
   A throttle is used to vary the load provided by the engine during operation, by the following means:

   - Reducing the **pressure** in the cylinder = reducing the mass of air in the cylinder = allows to control the heat release rate by unit cycle.
   - Reducing the **net imep** thanks to pumping losses.

2. **Why do SI engines operate at stoichiometry?**
   Need to:

   - During the start of ignition, you need to have a stoichiometric mixture so the kernel can propagate.
   - During final burn up, flame temperatures should be high to burn the whole mixture.
   - Oxidize HC and CO into CO_2.
   - Reduce NO to N_2 by catalytic conversion which operates near stoichiometry (requires low O_2 content in burnt gases).

3. **Why do CI engines operate lean?**
   To avoid incomplete combustion and smokes, **soot** (non-premixed combustion).

4. **Why is the crank angle over which combustion takes place independent of engine speed in SI engines?**

$$\Delta\theta = \frac{BN}{S_L k^{1/2}} \propto \frac{BN}{S_L N} \propto \frac{B}{S_L}$$

5. **Why is the bore and stroke equal in most automotive SI engines for land use?**
   To allow for the flame to propagate in a **sphere** which yields :

   - Better mixing.
   - Higher rate of combustion.
   - Lower heat losses.

6. **For a similar power output, why do CI engines have a higher sfc than SI engines?**
   CI engines operate at a higher compression ratio (since they're not limited by knocking), therefore higher net efficiency n_f, and lower sfc.

7. **Why are turbochargers used - advantages and disadvantages?**
   Turbochargers are used to **increase the power** in CI and SI engines by increasing the density of the intake air (compression + intercooling). The energy required to operate the turbocharger is extracted from exhaust gases (turbine which powers the compressor + intercooler).

- **CI engines:** Vary the total air charge at a fixed speed. Wider range of loads at low emissions (the latter are limited by lean equivalence ratios).
- **SI engines:** Can also benefit from turbocharging by downsizing the engine to a smaller maximum torque. We're basically able to achieve the same power output with a smaller cylinder which improves the efficiency.

Some drawbacks are:

- Cost (for SI engines specifically, throttling is simpler, lighter, and cheaper).
- Weight and need for an extra piece of equipment.
- It takes time for the turbocharger to spin up = turbo lag (compared with naturally aspirated engine) = Delay in response to torque demand by the driver + High PM emissions since air isn't delivered quickly enough, mixture in the cylinder is rich.
- Lower temperatures downstream the exhaust limit catalytic conversion efficiency.
- Sizing concerns: a small turbocharger will deliver good boost at low rpm but high boost at high rpm = must get rid of the excess energy using the waste gate (bypass the turbine) = less efficient.
- For SI engines: high pressure intake can lead to knock.

8. **What is pre-ignition, why does it occur?**
   Pre-ignition occurs in an SI engine when a flame is initiated before the spark plug. Conditions for it to occur:

   - There should be initial **hot spots**.
   - The size of the hot spot should be of the order of the **flame thickness** (condition for flame propagation from kernel). The flame thickness is given by the **laminar flame speed $\mathbf{S_L}$**.

   $$S_L \uparrow \longrightarrow \delta \downarrow \longrightarrow p(knock) \uparrow$$

9. **What is knock and superknock and why are they important?**

   - Knock is an abnormal combustion event in SI engines caused by autoignition of the mixture that isn't due to the spark plug, ahead of expanding flame front due to the spark plug. The pressure rise can damage the engine and reduce its efficiency.
   - Superknock occurs when the pressure wave of the expanding flame front due to the spark plug is coupled to the pre-ignition wave (pressure and temperature of hot-spots has to be high for this to happen), which can lead to engine and piston damage. Since superknock is a stochastic process, it won't necessarily happen in each cycle.

10. **What is the difference between residual gas recirculation and exhaust gas recirculation?**

- **Residual gas:** the remaining product gas inside the cylinder after each cycle. Large amounts of exhaust gas reduce the total power but can be helpful for emission reduction.
- **Exhaust gas recirculation:** Purposefully recirculating a portion of the burnt gases from the exhaust stream into the intake manifold in order to reduce the peak temperature.

11. **What are the main differences between SI and CI in the gas exchange process and valve timings?**
    No major differences except:
    - There is no role for exhaust gas recirculation in evaporating the incoming fuel.
    - Residual gases are less important.
    - Gas exchange process more defined by pressure + turbocharging.
12. **What is the volumetric efficiency?**
    Ability to replace the old mixture with the fresh mixture.
    Important: Include graph from lecture 2.
13. **Why replace a single-hole injection system with a multi-hole?**
    Droplets are smaller, they will evaporate quickly, and the equivalence ratio will brought down closer to stoichiometry = lower PM and NOx emissions.
14. **Why do we use standard air cycles?**
    Simple way of the understanding the importance of the compression ratio and throttling on engine indicated efficiency (burn duration, knock, heat transfer cannot be modelled).
15. **What are the main SI engine emissions and their sources?**
    - Hydrocarbons: Emitted in rich flames.
      - Temporary fuel-rich operation at engine startup (cold start).
      - Small concentrations of the quenched mixtures are stuck in small crevices between the piston and the cylinder.
      - Oxidation of HC is only partial (1-2% HC escapes during steady combustion operation).
      - HC can dissolve in oil. They are blown by the rings into the oil.
    - CO: emitted in rich flames.
      - Incomplete combustion, usually at cold start. Produced in rich pockets of unburnt gas (droplets).
      - Kinetics: The CO oxidation reaction into CO_2 is very slow. Once you form it, it doesn't oxidise easily (relating to previous point).
      - CO oxidation into CO_2 is slow below 1400 K and high above it. When operating in rich conditions, the flame temperature goes down, and the oxidation of CO slows down too.
    - NOx: emitted at high temperatures (thermal NOx).
      - Zeldovich mechanism.

- EGR can help reduce NOx.
- Operating at large speeds = lower residence time = less NOx.
- Late SOI or spark = lower pressure and temperature = less NOx.

16. **How to reduce emissions in SI and CI engines? What are the advantages and disadvantages of each method?**

- SI
  - **Three-way catalytic converters:** Convert HC, CO, and NO simultaneously. Blocks of temperature resistant ceramics coated by Pt/Pd/Rh and CeO_2. Switches quickly between lean and rich conditions (1 Hz):
    * **Lean** (Excess oxygen + O_2 which was stored by CeO_2): Oxidation of CO and HC to CO_2 and H_2O.
    * **Rich (HC is stored)**: Reduction of NO to N_2.

    Downsides:
    * Needs warmup ($T_{min} > 200\,C$) = Ineffective at cold start (where HC and CO emissions are highest).
    * At high temperatures ($T_{min} > 900\,C$), poisoning by sulphur in fuel or lubricant.
  - **EGR:**

    Advantages:
    * Reduces flame temperature = lower NOx emissions.
    * Increase efficiency by aiding load control without pumping losses.

    Disadvantages: Beyond 30%
    * Can cause misfire.
    * Can increase soot, CO, and HC emissions (local rich pockets?).
- CI