2.61 Internal Combustion Engine
Final Examination

Open book. Note that Problems 1 &2 carry 20 points each; Problems 3 &4 carry 10 points each.

Problem 1 (20 points)

Ethanol has been introduced as the bio-fuel entry to the transportation fuel market. We are to assess the charge cooling effect when ethanol is used in a 4-stroke direct injection spark ignition engine. Because of cold start consideration, E85 (which is 85% ethanol to 15% gasoline by volume) is used in practice. To simplify the problem, however, we'll compare the use of neat ethanol (i.e. E100) to gasoline (E0).

The gasoline has H to C ratio of 1.85, with an averaged molecular weight of 110, and latent heat of vaporization of 305 kJ/kg.

Ethanol is C_2H_5OH, with a molecular weight of 46 and latent heat of vaporization of 840 kJ/kg.

For both engines, injection takes place during the intake stroke. To simplify the problem, assume that at IVC, all the fuel has evaporated and mixed with air to form a homogeneous trapped charge, and the engine speed is sufficiently low so that the cylinder pressure at IVC is equal to the manifold absolute pressure (MAP). Furthermore:

- for the E0 engine, 30% of the liquid fuel lands on the wall and then evaporates (so that the latent heat is supplied by the wall), and 70% of the fuel evaporates in flight, thereby cooling the air;
- for the E100 engine, 50% of the liquid lands on the wall and then evaporates and 50% of the fuel evaporates in flight.

Both the E0 and E100 engines are operating at stoichiometric A/F. You may also neglect the residual gas.

a) Using the ideal gas law, show that the trapped mass of air m_a per cycle is

$$m_a = \frac{MAP * V}{\Re T\left[\frac{1}{W_a} + \frac{F/A}{W_f}\right]}$$ *(If you do not finish this part, just use the formula for the rest of the problem)*

where V and T are the volume and temperature of the trapped charge at intake-valve-closing; W_a and W_f are the molecular weights of the air and the fuel, $\Re$ the universal gas constant, and F/A is the fuel to air ratio. Identify the cooling effect and the fuel vapor displacement-of-the-air effect.

b) To assess the displacement effect only: if the trapped charge temperature are the same, what would be the ratio of m_a for the engine using E100 and using E0?

c) The trapped charge temperature T will be different with the two fuels. What are the temperature drops, ΔT, for using the two fuels due to evaporative cooling? In this calculation, since the mass of fuel is small compared to that of the air, you may assume that the fuel does not contribute significantly to the sensible energy of the charge except for the latent heat of vaporization. The specific heat at constant pressure for the air is 10^3 J/kg-K

d) If the temperature of the charge without accounting for the evaporative cooling (i.e. the ΔT in part c) is 40°C (313K), what is the ratio of m_a for using the two fuels when both the fuel vapor displacement and the charge cooling effects are accounted for?

e) If the end gas for both fuels follows a polytropic efficiency n=1.32 (i.e. pV^n=constant), what are the end gas temperatures for using the two fuels when the MAP is 1 bar and the end gas pressure is at 80 bar?

Problem 2 (20 points)

An effective way to improve the engine efficiency is to turbo-charge-downsize the engine. Then at part-load, the engine works at a higher load point so that the pumping loss is less and the parasitic losses (heat transfer, rubbing friction, ...) relative to the fuel energy are reduced. We are to look at the scaling law of the parasitic losses with respect to the size of the engine.

All engine geometric dimensions (such as stroke, clearance height, piston skirt, ...), with the exception of the piston rings, scale with the bore (B). The ring thickness (h), however, remains unchanged as the engine size changes.

We are to compare engines with different values of B operating at the same speed (N revolution/sec) and torque (Γ) output. As the engine is downsized (decreasing B) at the same Γ, the engine will be running at a higher MEP. However, it could be assumed that the charge temperature in the cycle is approximately the same since the higher heat release rate per unit volume at the higher load is counter-acted by the higher thermal mass per unit volume.

(a) We'll consider the heat transfer scaling. The engine heat transfer is governed by the Nusselt number correlation

$$Nu = a\, Re^{0.8}$$

where a is a proportional constant. The Reynolds number Re is based on the mean piston speed and B. The Nusselt number Nu is based on B. Both the kinematic viscosity μ and thermal conductivity k of the working fluid may be considered as unchanged since the cycle temperature does not change appreciably with the downsizing (μ and k are not sensitive to pressure).

How does the heat transfer per cycle Q scale with B?

(b) The top ring friction is considered here. The reciprocating friction is dominated by the hydrodynamic part of the motion. The hydrodynamic frictional coefficient f is proportional to the square root of the Sommerfeld number S defined by

$$S_R = \frac{\mu_L U}{\sigma_R h}$$

where μ_L, the viscosity of the lubricant, may be considered unchanged since the cycle temperature is approximately the same. The velocity U is the mean piston speed; h is the ring thickness, and the normal stress σ_R on the ring is due to the pushing of the ring against the liner by the cylinder pressure.

How does the top ring frictional work done per cycle scale with B?

(c) The piston skirt friction is considered here. Again the friction is dominated by the hydrodynamic part of the motion with the frictional coefficient governed by the Sommerfeld number S_S similar to that in part (b).

$$S_S = \frac{\mu_L U}{\sigma_S H}$$

However, the length scale is now H, the skirt height, which scales with B, and the normal stress σ_S is now due to the pushing of the connecting rod on the piston against the liner.

How does the piston skirt frictional work per cycle scale with B?

Problem 3 (10 points)

In many of the severe knock occurrences, there is substantial damage to the top land of the piston because the knock-induced shock wave in the combustion chamber enters the top land crevice and detonates the fuel air mixture there; see picture.

(i) Explain why detonating the top land crevice gas would produce more damage than detonating the combustion chamber mixture?

(ii) For a typical piston top land crevice geometry (land height = 6mm; piston/liner clearance = 150 μm), and wall temperature of 500K, if the pressure of the crevice gas is 40 bar just prior to the detonation, estimate the crevice pressure induced by the detonation for an engine operating at λ =1 and with negligible residual gas. The crevice gas (both burned and unburned) may be modelled as an ideal gas with γ = 1.32 and molecular weight of 29. (Hint: apply 1st Law of thermodynamics to the crevice gas, and note that c_v=RT/(γ -1)).

Problem 4 (10 points)

You are asked a venture capital firm to evaluate a proposed engine technology; see below. (The materials are from a real company in US, and could be downloaded from the web at http://www.scuderigroup.com/.)

The basic concept of the engine is a split cycle; i.e. the engine uses a separate cylinder for compression and expansion. At the end of the compression stroke, the compressed charge is transferred from the compressor to the expander through the crossover passage. The timing of the transfer is controlled by the transfer valves. The fuel can either be injected in the intake, or in the crossover passage. The combustion takes place in the expander.

Make 5 technical comments about this technology. Each comment can either be positive or negative respectively, but these comments should be based on sound physical principles.