Homework Set #8

Problems:

1)   The following exercise is for you to get a feel for the magnitude of things for a modern turbo-charged truck diesel engine. The Hino K13C 4-stroke turbo-charged diesel engine has the following specifications:

No. of cylinders	6
Total displacement	12882 cc
Bore x Stroke	135 mm x 150 mm
Compression ratio	16.5
Rated power	294 KW @2000 rpm
bsfc @ rated power	200 g/KW-hr
Injection: common rail; max pressure	1400 bar
Nozzles	8 per injector @ 200 µm diameter each
Compressor pressure ratio at rated power	2.5
Intercooler outlet temperature at rated power	120° C

At rated power, the volumetric efficiency is approximately 0.8. The fuel pulse width is 40° crank angle. We'll assume that the injection rate is constant (at the average value) for the following analysis. (The actual needle lift profile has a triangular shape delivery rate.)

Compute the following quantities at rated power: (You may assume that the cylinder condition at the time of injection to be 50 bar and 800K.) Diesel fuel at 120° C (the fuel operating temperature) has s.g. = 0.78 and viscosity = 5×10^{-4} N-s/m^2.)

(a)   What are the air mass flow rate and the average fuel flow rate for the engine? What is the A/F?
(b)   On a per cylinder, per cycle basis, what are the air mass, the fuel mass and fuel volume injected per cycle? (You should get a mental picture of these quantities.)
(c)   What is the average flow velocity through each nozzle hole?
(d)   If the nozzle hole has a length to diameter ratio of 10, what is the pressure drop? Is this drop significant?
(e)   What is the average discharge coefficient for each nozzle?
(f)   If the critical Webber number is 30, what is the average droplet diameter of the diesel spray? (The surface tension of the diesel fuel at the injection condition is 0.025 N/m.)
(g)   If all the drops are of the same size as calculated in (f), how many drops are there? If these drops are to be distributed uniformly in the cylinder at TDC, what is the average distance between the drops? What is the implication of these facts on the air/fuel mixing process? (Neither assumption is a good one, but the estimates give a picture of the difficulty of air utilization.)

2)   The compression ratio of a diesel engine must be high enough for fast auto-ignition. An acceptable ignition delay is 20° crank angle. We'll use the ignition delay equations – Eq. (10-37, 38 and 39) to study this. The inlet pressure and temperatures are 1 bar and –20°C (253K). The cranking speed is 200 rpm. The fuel has a cetane number of 45.
There is a typo in Eq. 10-37; a + sign is missing between the two ( )'s. The correct equation is

$$\tau_{id}(CA) = (0.36 + 0.22\bar{S}_p)\exp\left[E_A\left(\frac{1}{\bar{R}T} - \frac{1}{17,190}\right) + \left(\frac{21.2}{p-12.4}\right)^{0.63}\right]$$

(a)   For a truck engine with a 135 mm stroke at this low ambient temperature, the polytropic exponent (n) for compression is 1.2. Plot the ignition delay as a function of compression ratio (CR) in the range of 12 to 25. Determine the minimum CR required.
(b)   For a small passenger car diesel engine with a stroke of 80 mm, because of the higher heat loss, n = 1.12. Plot the ignition delay on the same graph as in (a) and determine the minimum CR required.

3)   The soot burn-up rate may be obtained by the Nagle and Strickland-Constable formula which is given by Eq. (11.41),(11-42) and Table 11.10 of the text. The value w in the formula is the surface oxidation rate in g/cm^2-s. Since the data for the correlation were obtained from graphite oxidation experiments, the rate is the value for carbon. We'll assume that the oxidation of soot particle is at the same rate as that of carbon. Also the density of the soot is assumed to be 2 g/cc.

Do the calculations for the following conditions:
       (a) p=100 bar and T = 2500 K
       (b) p=70 bar and T = 2000 K
       (c) p=30 bar and T = 1400 K
The three conditions represent roughly at the peak pressure point, at the end of combustion, and late in the expansion process.

(i)   To show that mass transport is not the limiting process for oxidation of small particles, calculate the transport time ($\tau = d^2/D$) for particle diameter d of 10, 100 and 1000 nm. The mass diffusivity D is:

$$D(m^2/s) = 1.8 \times 10^{-5} (\frac{p_0}{p})(\frac{T}{T_0})^{1.81} \text{ where } p_0 = 1 bar \text{ and } T_0 = 300K$$

(Note that the mean free paths (λ) under these conditions are of the order of 50 nm. Therefore the 10 nm particle would be in the free flow or Knusen regime for which the transport time is approximately $\tau \sim (d^2/D)*\lambda/(3d)$, which is not that different from the estimate by using just d^2/D.)

(ii)   Calculate the time to oxidize particle of diameter 100 nm for oxygen mole fractions of 0.1%, 1% and 10%. Note that to have fast oxidation, sufficient oxygen has to be available at high temperatures.

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Spring 2017