AME 436
Midterm Exam #1 Study Guide
February 22, 2018

Format of the exam

90 minutes allowed. Open book exam to the extent of hard copies of the lecture notes, your personal notes, homework sets and solutions and the (optional) textbooks **only**. Laptop computers are NOT permitted for any reason (even to view pdfs of lecture notes), but calculators are. Show all work; partial credit given if you can show you have a valid approach!

Material covered

The exam may cover any material through lecture 5. This includes:

- Introduction
    - Classifications of IC engines
    - Advantages and disadvantages of each type
    - Alternatives to IC engines and hydrocarbon fuels
    - History and evolution
    - Where room for improvement is and isn't

- Fuels and combustion
    - Fuel types
    - Chemical thermodynamics
        - Balancing chemical reactions (stoichiometry, fuel mass fraction, equivalence ratio)
        - 1^{st} Law of Thermodynamics for a chemically reacting system
            - Heating value
            - Adiabatic flame temperature
        - 2^{nd} Law of Thermodynamics for a chemically reacting system
            - Degrees of Reaction Freedom (DoRFs)
            - Chemical equilibrium
            - Isentropic compression/expansion
                - Entropy of a gas mixture
                - Frozen and equilibrium expansion
    - Combustion
        - Chemical reaction rates
            - Law of Mass action
            - Arrhenius term – $e^{-E/\Re T}$ – responsible for extreme sensitivity of reaction rates to temperature whenever $E/\Re T >> 1$ (say 5 or more)
        - Premixed flames
            - Deflagrations
                - Burning velocity – depends mostly on T_{ad}
                - Effects of turbulence
                - Homogeneous reaction – depends mostly on T_∞
        - Non-premixed flames
            - Droplets
            - Gas-jets

- Pollutant formation and remediation
    - Which emissions are bad?
        - Atmospheric photochemical cycle
        - Greenhouse effect
        - Emissions regulations
    - Emissions are a non-equilibrium phenomenon – if everything went to equilibrium there would be no emissions!
        - NO_x
            - Thermal or Zeldovich NO
                - Formed at high T - very high activation energy process
                - Slow time scale – forms in products, not in flame itself
                - Lean mixtures (surplus O) favors NO formation
                - Rich and cool better (no excess O_2), low temperatures
            - Prompt NO
                - Formed in the flame
                - Two mechanisms
                    - Reaction between N_2 and CH or C_2 radicals
                    - Reaction between N_2 and super-equilibrium concentrations of O atoms with flame
        - CO, unburned hydrocarbons (UHC), formaldehyde (CH_2O)
            - Formed due to incomplete combustion or "trapped" fuel (e.g. crevice volumes)
            - High T and excess O_2 needed to minimize emissions – oxidize CO to CO_2 and UHC/CH_2O to CO_2 and H_2O
    - Soot
        - Premixed **(actually I glossed over this part in lecture, so I won't include this on the midterm)**
            - Only formed in rich mixtures, in combustion products
            - Critical equivalence ratio
            - More soot at lower temperatures because soot formation must compete with oxidation
            - Doesn't depend on fuel structure because fuel is destroyed in flame front – molecules have to reassemble in combustion products
        - Nonpremixed **(this I did cover so is "fair game.")**
            - Forms on rich side of flame front
            - More soot at higher temperatures because no competition between formation and oxidation
            - Depends on fuel structure because fuel molecules not destroyed by flame front before soot can form
    - Cleanup
        - Premixed - CO, UHCs main concern
            - Burn at stoichiometric with EGR to reduce flame temperature
            - 3-way catalyst, oxidizing for CO, UHC, CH_2O, reducing for NO
        - Nonpremixed – NO, soot main concerns
            - Can't use 3-way catalyst since mixture is lean overall – won't reduce NO
            - Need particulate traps for soot, Selective Catalytic Reduction for NO

Sample midterm exam (problems should look familiar…) (average was 66/100)

Problem #1 (chemical thermodynamics) (50 points total)

On Titan, one of Jupiter's moons, is an atmosphere of pure C_3H_8 at 0.2 MPa (2 earth atmospheres) pressure at a temperature of 240K. Deep underground are deposits of 40 mole percent O_2 and 60 mole percent N_2 that the Titans pump out of the ground. Unfortunately, most of the O_2/N_2 wells are located in politically unstable regions of Titan, so this O_2/N_2 mixture is a valuable resource which they call "fuel." The propane in the atmosphere, which they call "air," is "free" as far as Titans are concerned.

Thermodynamic data: average mixture properties $\gamma = 1.35$, $R = 290$ J/kgK, $C_P = 1120$ J/kgK

	C_3H_8	O_2	N_2	CO_2	H_2O	N
Δh_f^o (kJ/mole)	-104.7	0	0	-393.52	-241.83	+472.68
Molecular mass (g/mole)	44	32	28	44	18	14
K (equilibrium constant) at 2200K (dimensionless)	2.043×10^{-14}	1	1	2.037×10^{3}	1.644×10^{1}	1.238×10^{-8}

a) **(10 points)** What is the stoichiometric "fuel" to "air" mass ratio (FAR) assuming the combustion products are CO_2, H_2O and N_2? **(Watch units – g vs. kg vs. moles, kJ vs J, etc.)**
b) **(10 points)** What is the heating value (in J/kg) of the 40% O_2 / 60% N_2 "fuel" that Titans burn with C_3H_8?
c) **(10 points)** What is the **constant-pressure** adiabatic flame temperature of "fuel' + "air" mixtures with equivalence ratio (ϕ) = 0.8 ?
d) **(10 points)** The main product of stoichiometric fuel-air combustion (other than N_2, CO_2, H_2O) is N atoms, which are extremely toxic to Titans. Suppose that after combustion, the temperature of the products mixture were increased or decreased to 2200K (but still kept at 2 atm total pressure). Assuming that the mole fraction of N atoms (X_N) << 1, estimate the value of X_N at equilibrium.
e) **(5 points)** Relative to flames on earth, do stoichiometric **premixed** flames on Titan produce more or less CO emissions due to incomplete combustion? Explain why – no credit without explanation.
f) **(5 points)** Relative to flames on earth, do **nonpremixed** flames on Titan produce more or less soot? Explain why – no credit without explanation.

Problem #2 (50 points, 5 points each part)

On Planet X (which is completely unrelated to Titan), the atmospheric pressure is exactly half that of earth's atmosphere. All other properties of the atmosphere, specifically the ambient air temperature (T_∞), composition (O_2 + 3.77 N_2), thermal conductivity (k), heat capacities (C_P, C_v) are exactly the same as on earth. How would each of the following properties be different on Planet X than on earth? In particular, state whether the property increase or decrease and by a factor of less than, more than, or exactly a factor of 2. In some cases there may be no change at all. **No credit without explanation.**

a) Stoichiometric fuel mass fraction (f) for methane burning in air
b) Heating value of methane burning in air
c) Constant-volume adiabatic flame temperature of methane burning in air
d) Laminar burning velocity of a stoichiometric methane-air mixture
e) Turbulent burning velocity of a stoichiometric methane-air mixture (assume u' same on earth as on Planet X)

f) Time for homogeneous explosion in a stoichiometric methane-air mixture
g) Length of a nonpremixed laminar gas-jet flame
h) Length of a nonpremixed turbulent gas-jet flame
i) Rate of thermal NO formation immediately behind a stoichiometric premixed methane-air flame
j) Concentration of NO far downstream of a stoichiometric premixed methane-air flame, i.e. at equilibrium, assuming perfectly adiabatic conditions