AME 514 – Applications of Combustion – Spring 2015
Final Exam 5/12/2015

Time allowed: 2 hours. Each problem is worth 25 points. **Do any 4 of the 5 problems. You can try all of the problems, but turn in only 4 to be graded.** The exam is open book and notes - use any reference materials you want. Calculators are allowed, but laptop computers are **not** allowed. Write on the exam pages and use the back sides of the pages if you need more space.

1. Anything goes

Planet X is identical to earth **in every way** except that the ambient atmospheric pressure on Planet X is **half that on earth**. The ambient air temperature is still 300K and the atmospheric composition is still 21% O_2 and 79% N_2 as they are on earth. How would each of the following be different on Planet X? In particular, does the property increase, decrease or remain the same, and if it changes, does it change by more than, less that or exactly a factor of 2? **Explain each in 1 or 2 sentences. No credit without explanation. Each part is worth 3 points, 1 point is free.**

a) The burning velocity at the extinction limit ($S_{L,lim}$) for a lean premixed methane-flame in a large tube at microgravity, where extinction is due to radiative losses
b) The amount of thermal NO emission in a stoichiometric premixed methane-air flame, very far downstream of the flame where equilibrium conditions have been reached
c) The minimum **mass flow rate** required to sustain combustion in a microscale counter-current (or Swiss roll) heat exchanger and combustor (assuming the same combustor size, mixture and fuel mass fraction on earth and on X).
d) The NET power output of the Berkeley micro Wankel engine
e) The turbulent burning velocity (S_T) of a stoichiometric fuel-air mixture in the distributed combustion regime, assuming Damköhler's model is correct, and assuming u' and L_I are same on earth and on Planet X).
f) Liftoff height of a turbulent round jet (same jet diameter d_o and mass flow rate as earth-based jet), assuming the scaling given in the lecture notes is correct.
g) The **thrust of a steady-flow hypersonic propulsion engin**e with constant-area heat addition followed by constant-temperature heat addition until the exit pressure equals the ambient pressure (corresponding to problem 5 on HW #4), assuming same flight Mach number and inlet area (you don't have to do all the calculations, just explain your result.)
h) The **specific impulse of a pulse detonation engine**

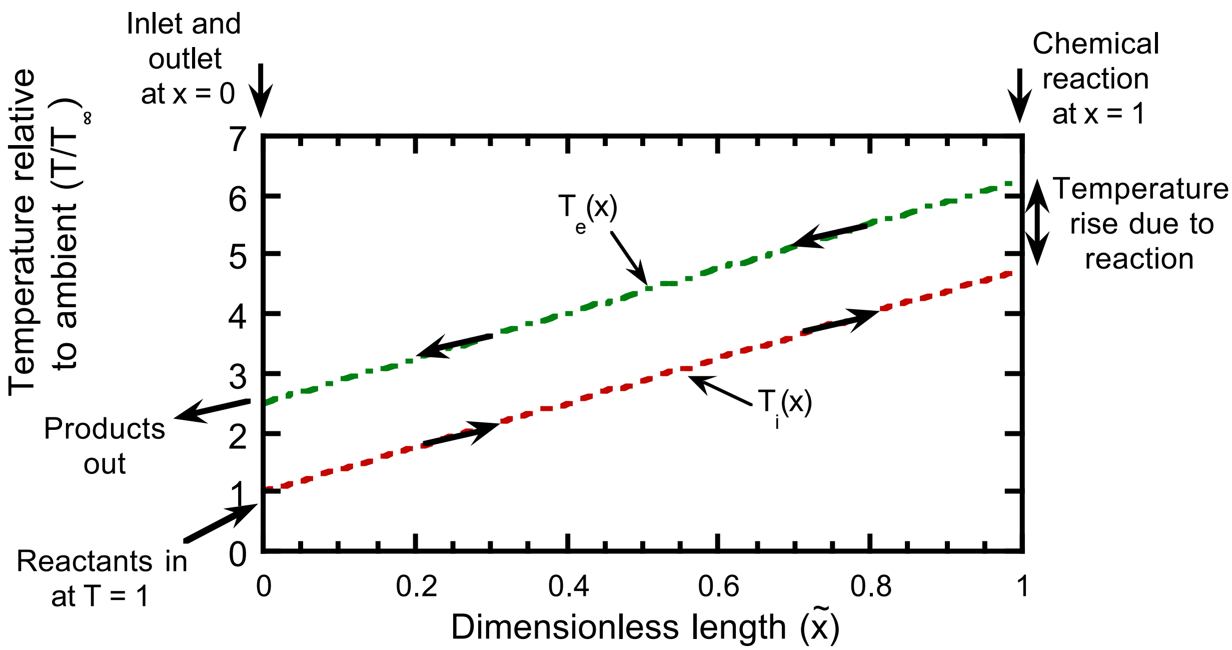
2. Advanced fundamental topics – flammability, ignition, pollutant formation

Ronney Oil and Gas Co. claims to have invented a new fuel additive, called PDR®, which **decreases the fuel heating value (Q_R) by 10%** but has **no effect on any other chemical, thermodynamic or transport property.** Estimate by what percent each of the following combustion properties would increase or decrease by adding PDR® to propane (C_3H_8) in each of the following cases (i.e. is there less than 10% change, exactly 10% change, or more than 10% change). In some cases there may be no change at all. **Explain each in 1 or 2 sentences. No credit without explanation. Each part is worth 3 points, 1 point is free.**

a) Flame-front temperature of a non-premixed C_3H_8-air flame under diffusion-controlled burning conditions
b) Extinction stretch rate of a nonpremixed C_3H_8-air flame
c) The burning velocity **at the upward flammability limit** ($S_{L,lim}$) of a lean premixed C_3H_8-air flame in a large diameter tube at earth gravity.
d) The fuel concentration **at the radiation-induced flammability limit** of a lean premixed C_3H_8-air flame with negligible buoyancy effects
e) The minimum ignition energy of a stoichiometric premixed C_3H_8-air mixture
f) The amount of soot production in a rich premixed C_3H_8-air flame at equivalence ratio 1.4
g) The amount of soot production in a nonpremixed laminar C_3H_8 jet flame
h) Amount of prompt NO emission in a rich premixed C_3H_8-air flame at equivalence ratio 1.4

3. Microscale combustion

Consider a linear counter-current heat exchanger and combustor as described in Lecture 4, slides 41 - 50. The temperature profiles for the reactant gas and product gas (dividing wall temperature profile is excluded for clarity) are shown in the attached figures for the special case of no heat loss, no streamwise wall heat conduction and infinitely fast chemical reaction rates. (This is just a reproduction of the figure on page 44.) Below is an expanded diagram just to help refresh your memory about the meaning of this plot.



Show modified temperature profiles for each of the following modifications to this ideal combustor. **Explain each answer in a few sentences.**

(a) The combustor is taken to Planet X where the pressure is half that on earth (same combustor dimensions, inlet flow velocity and fuel mass fraction)

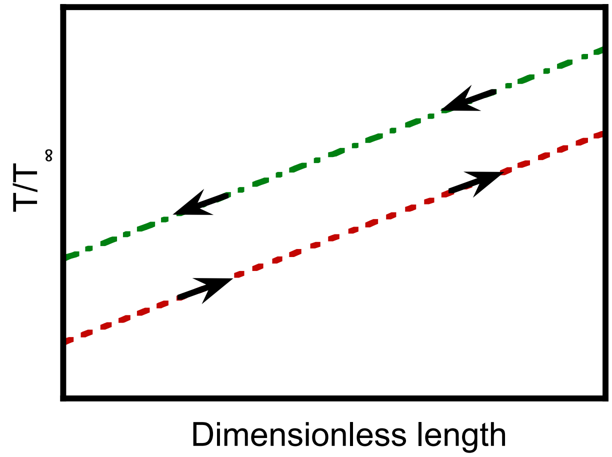
(b) The PDR® fuel additive of Problem 2 is used which decreases the fuel heating value by 10%

(c) The reactant side is experiences significant heat losses (product side is still adiabatic)

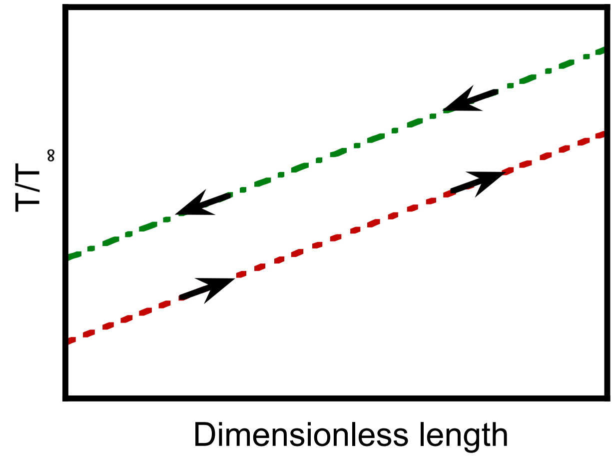
(d) The nitrogen in the air is replace with a gas having a much lower thermal conductivity, but all other properties of the gas are the same as nitrogen

(e) The dividing wall is made perfectly non-conducting, so that there is no conduction in either the streamwise (i.e. parallel to the flow direction) or spanwise (i.e. from products to reactants) direction.

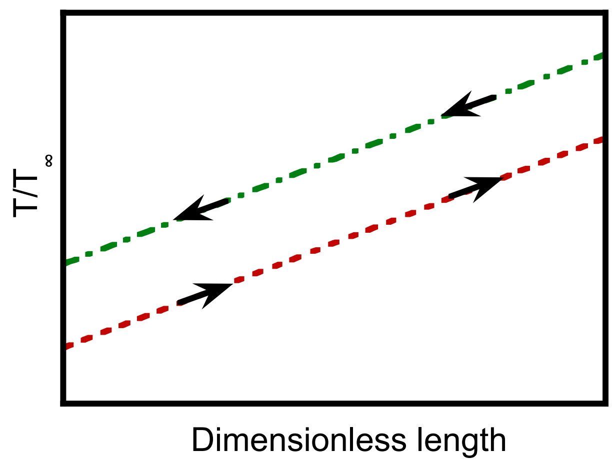
Problem #3. **Name** ________________________



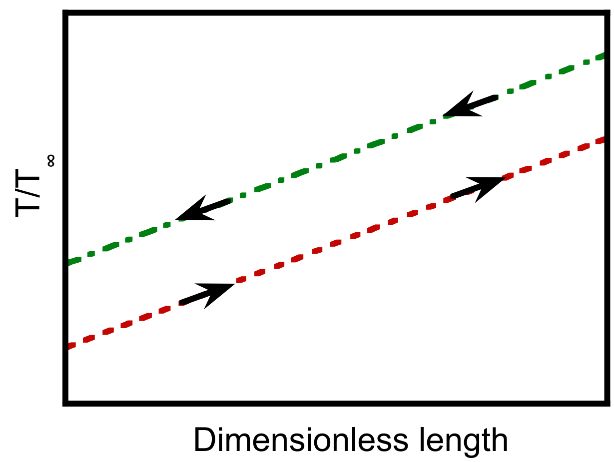
(a) *Planet X – 0.5x pressure*



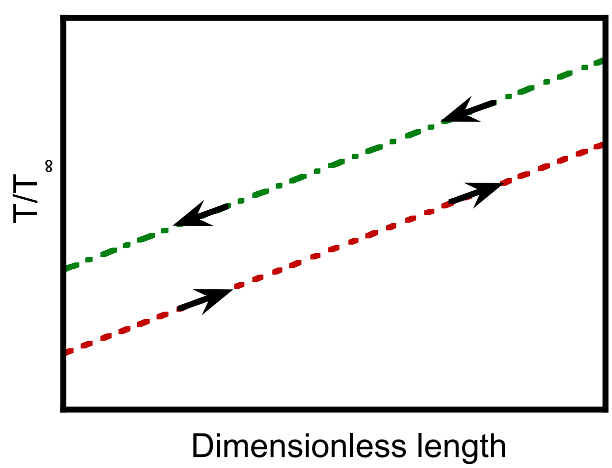
(b) *PDR® added – 10% decrease in Q_R*



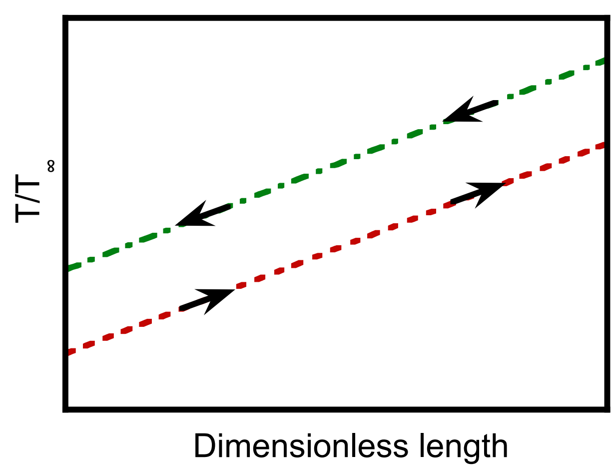
(c) Significant heat losses on reactant side only



(d) N_2 replaced with low-conductivity gas



(e) The dividing wall is non-conducting



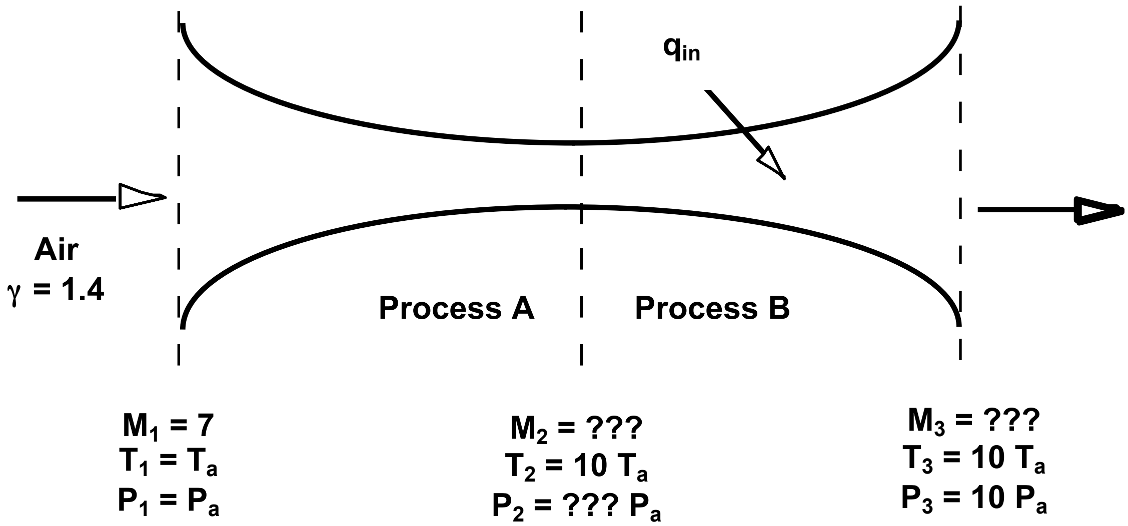
Spare in case you mess one up – state which one you're doing here!

4. Turbulent combustion (5 points each part)

Consider a turbulent premixed flame in a lean methane-air mixture whose laminar burning velocity (S_L) is 10 cm/s. The integral length scale of turbulence is 5 cm. Use the following mixture properties if needed: air density (ρ) = 1.18 kg/m^3, viscosity (ν) = 1.5 x 10^{-5} m^2/s, thermal diffusivity (α) = 2.2 x 10^{-5} m^2/s.

a) What is the minimum turbulence intensity (u') that would be required to extinguish this flame if extinction occurred according to Bradley's criteria, namely $Ka = 0.079\ Re_L^{1/2}$ (if $Re_L < 300$) or $Ka = 1.5$ (if $Re_L > 300$). (You need to decide which of these 2 criterion yield the lower u' at extinction.)
b) What would the Kolmogorov length scale be at this condition?
c) If you used instead a stoichiometric methane-air mixture whose burning velocity is 40 cm/s, what combustion regime would this turbulent flow field produce?
d) For this stoichiometric mixture, what would the turbulent burning velocity be? (Use any model you want that is appropriate for the combustion regime you decided on in part c).
e) If you used a turbulent jet flow (like that analyzed in the context of nonpremixed turbulent flames in Lecture 9), what jet exit diameter (d_o), exit velocity (U_o) and downstream distance (x) would provide the required u' and L_T. (Note that there may be more than one suitable combination of d_o, U_o, and x, any one that works is acceptable)

Problem #5 (hypersonic propulsion)



Consider a simple hypersonic propulsion system for an aircraft at an initial Mach number of 7 that consists of two processes:

> **Process A**: Decelerate the incoming flow reversibly and adiabatically until the static temperature is 10 times the ambient temperature T_a
>
> **Process B**: Add heat at constant temperature until the pressure is equal to 10 times the ambient pressure

Assume that the gas is ideal with constant C_P, $\gamma = 1.4$ and that the fuel-to-air ratio (FAR) << 1.

a) Compute the Mach number after deceleration (station 2)
b) Compute the static (not stagnation) pressure relative to P_a after deceleration (station 2)
c) Compute the Mach number at the exit (station 3)
d) Compute the non-dimensional specific thrust
e) Compute the overall efficiency
f) Are the area changes between stations 1 and 2 and between stations 2 and 3 shown in the figure qualitatively correct? Why or why not?