AME 514 – Applications of Combustion - Fall 2006
Final Exam 12/11/2006

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, but no laptop computers, Pocket PCs, PDAs or other devices capable of running excel spreadsheets.

1. Anything goes

Planet X is identical to earth **in every way** except that the ambient atmospheric pressure on Planet X is twice 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. **Each part is worth 3 points, 1 point is free, do only 8 of 10 parts. Cross out or don't do the 2 parts you don't want graded.**

a) The minimum tube diameter for which a stoichiometric methane-air flame will propagate without quenching
b) The amount of thermal NO emission in a lean premixed fuel-air flame at equivalence ratio 0.9.
c) The relative importance of streamwise wall heat conduction compared to convection in a microscale counter-current (or Swiss roll) heat exchanger and combustor (assuming the same combustor size, mixture and mass flow rate 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 laminar flamelet regime (assuming Gouldin's fractal model of S_T is the valid one, and assume u' and L_I 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 engine with isentropic inlet and constant-temperature heat addition until the exit pressure equals the ambient pressure (corresponding to problem 1c-d 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 pulsed detonation engine
i) The minimum tube diameter for which a polymerization front in a fixed composition of acrylic acid – ammonium persulfate – water can propagate without quenching
j) The compression ratio in an HCCI engine where the rapid reaction (call it "ignition" "knock" "explosion" or whatever) occurs.

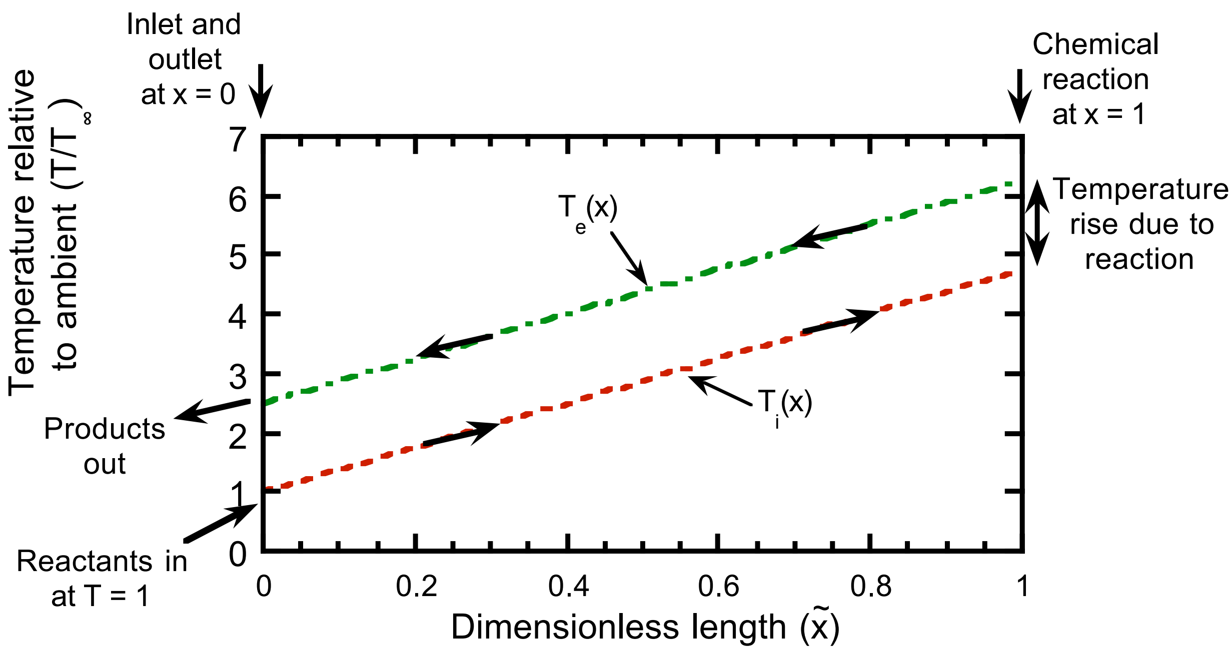
2. Advanced fundamental topics – flammability, ignition, pollutant formation

Ronney Oil and Gas Co. claims to have invented a new fuel additive, called PDR®, which **increases 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. **(Again, 3 points per part, 1 part free, but do all parts in this case.)**

a) Flame-front temperature of a non-premixed C_3H_8-air flame under diffusion-controlled burning conditions
b) Extinction stretch rate of a premixed C_3H_8-air flame
c) The burning velocity **at the downward flammability limit** ($S_{L,lim}$) of a lean premixed C_3H_8-air flame in a large diameter tube.
d) The burning velocity **at the radiation-induced flammability limit** ($S_{L,lim}$) of a lean premixed C_3H_8-air flame with negligible buoyancy effects
e) The adiabatic flame ball radius in 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 in the products of a rich premixed C_3H_8-air flame at equivalence ratio 1.4, far downstream of the flame where chemical equilibrium is reached, with N_2 added to obtain the same adiabatic flame temperature as a C_3H_8-air mixture without PDR® additive

3. Microscale combustion

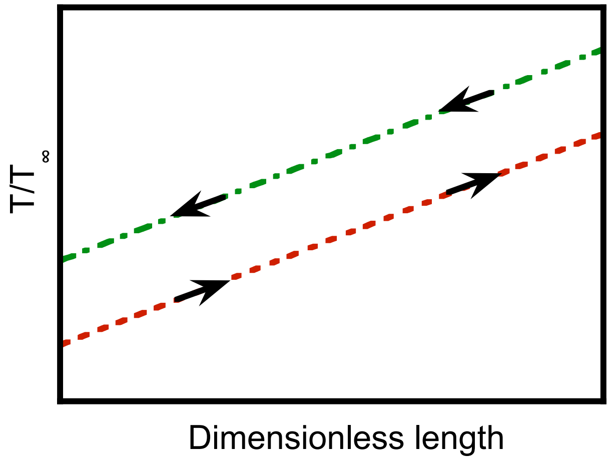
Consider a linear counter-current heat exchanger and combustor as described in Lecture 4, slides 42 - 48. The temperature profiles for the reactant gas and product gas (dividing wall temperature profile is excluded for clarity) are shown in the attached figures for the special case of no heat loss, no streamwise wall heat conduction and infinitely fast chemical reaction rates. (This is just a reproduction of the top figure on page 46.) Below is an expanded diagram just to help refresh your memory about the meaning of this plot.



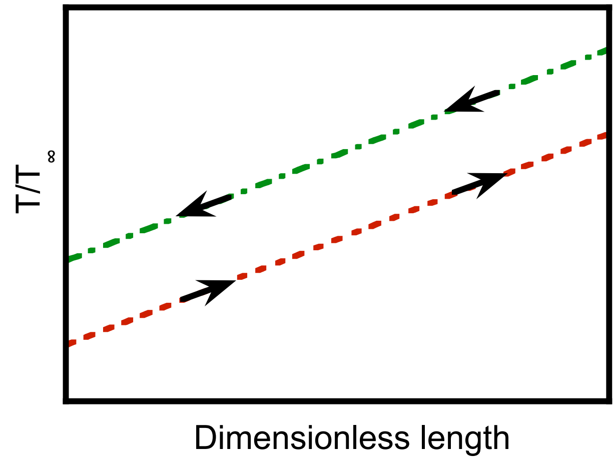
Show modified temperature profiles for each of the following modifications to this ideal combustor. **Explain each answer in a few sentences. Do only 4 of 5 parts. Be sure to turn in page 4 if you do this problem!**

(a) A different fuel with a much slower reaction rate is used, i.e. the reaction is close to extinction.
(b) The walls are roughened to make the flow turbulent in both the reactant and product streams.
(c) 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.
(d) The walls are coated with a high-emissivity material, so that radiative heat transfer between the center dividing wall and the outer walls increases greatly (but there is still no radiative or from the gas, and no heat loss to ambient).
(e) The mass flow rate is doubled (same mixture composition).

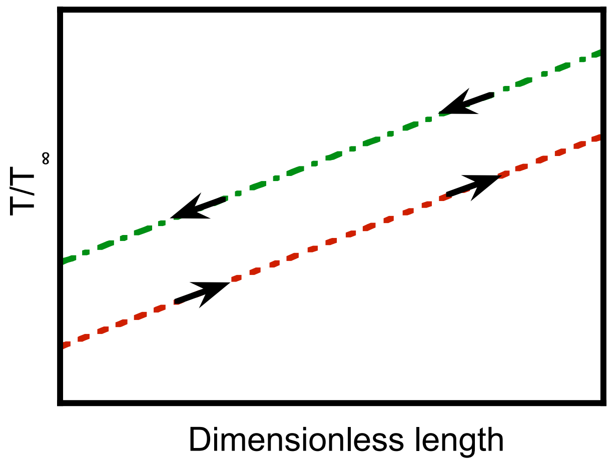
Problem #3. Name ________________________ (Do only 4 of 5 parts)



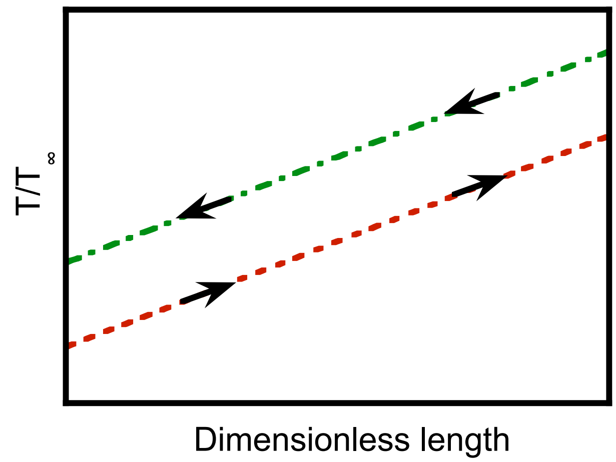
(a) *A fuel with slower reaction rate is used*



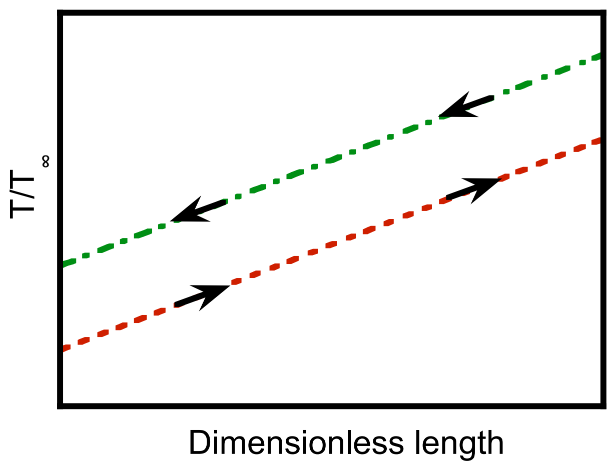
(b) *The walls are roughened - turbulent*



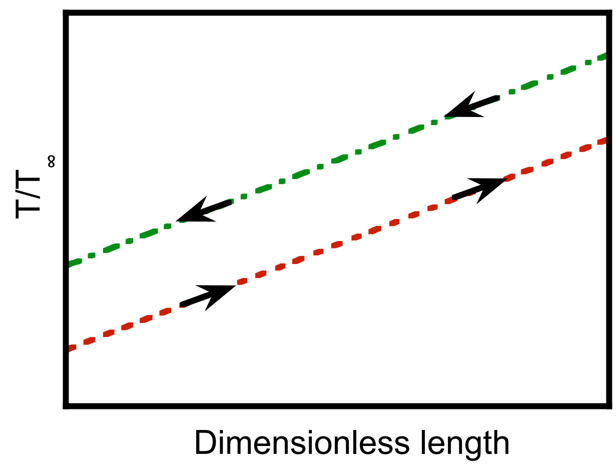
(c) The dividing wall is non-conducting



(d) The walls are coated with a high-ε material



(e) The mass flow rate is doubled (same mixture composition)



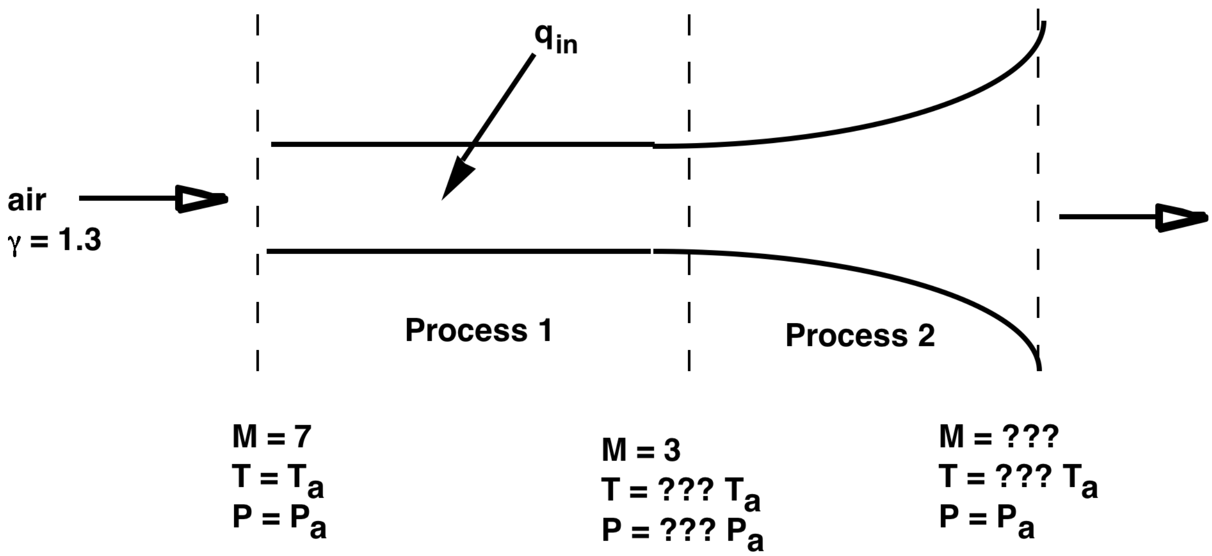
Spare in case you mess one up – state which one you're doing here!

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 = 0.10 m/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 turbulence intensity (u') would be required to extinguish this flame if extinction occurred according to Bradley's criterion, namely $Ka = 0.37\ Re_L^{1/2}$?
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 10), what jet exit diameter (d_o), exit velocity (U_o) and downstream distance (x) would provide the required u' and L_I? (Note that there may be more than one suitable combination of d_o, U_o, and x.)

Problem #5 (Hypersonic propulsion) (4 points each part, 1 point free)



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

Process 1: Heat addition at constant area from M = 7 to M = 3
Process 2: Isentropic expansion back to $P_e = P_a$

a. Compute the static (not stagnation) temperature relative to ambient temperature (T_a) after process 1
b. Compute the static (not stagnation) pressure relative to ambient pressure (P_a) after process 1
c. Compute the Mach number after process 2
d. Compute the static (not stagnation) temperature relative to T_a after process 2, and compute the specific thrust
e. Would an isentropic inlet to decrease the Mach number from 7 to 4, followed by heat addition to M = 3, change the Specific Thrust? (You don't have to show numbers, just state whether ST increases, decreases or stays the same and explain why.)
f. Would an isentropic inlet to decrease the Mach number from 7 to 4, followed by heat addition to M = 3, change the Thrust Specific Fuel Consumption? (You don't have to show numbers, just state whether TSFC increases, decreases or stays the same and explain why.)