AME 514 Applications of Combustion – Spring 2017

Assignment #2

Due Friday 3/10/17, 4:00 pm, in the drop box in OHE 430N (Xerox room in the OHE 430 suite of offices.) While hard copies are preferred, if you're off campus you can email your assignment to ronney@usc.edu. DEN students should submit through the usual channels. ***Late homework marked down 10 points (out of 100 possible) per day late.***

Part 1: paper review

Read any one of the research papers listed below, following the format given in the first homework assignment. Most of these papers are available in the "papers" folder in the lecture note folders on the course website. *If you have another paper relevant to the subjects of lectures 4 – 6 that you'd really like to read instead of one of my references because it relates to your research or work, I'll consider it, but you'll have to get my approval in advance.*

Deutschmann, O., Schmidt, R., Behrendt, F., Warnatz, J., Proc. Comb. Inst. 26:1747-1754 (1996). (Excellent paper on catalytic combustion modeling.)

Kaisare, N. S., Deshmukh, S. R., Vlachos, D. G. (2008). "Stability and performance of catalytic microreactors: Simulations of propane catalytic combustion on Pt." Chemical Engineering Science 63, pp. 1098 – 1116. (Excellent paper on simplified modeling of catalytic combustion.)

Lloyd, S.A., Weinberg, F.J., Nature 251:47-49 (1974) **and** Lloyd, S.A., Weinberg, F.J., Nature 257:367-370 (1975). (Key papers introducing the world to "Swiss roll" combustors – more than any other papers, the ones I wish **I** had written. ***Both papers are very short, treat the two papers as one*****).**

T. Hibino, A. Hashimoto, T. Inoue, J.-I. Tokuna, S.-I. Yoshida and M. Sano, "Single-Chamber Solid Oxide Fuel Cells at Intermediate Temperatures with Various Hydrocarbon-Air Mixtures," Journal of The Electrochemical Society, 147 (8) 2888-2892 (2000) (Key paper on single chamber solid oxide fuel cells; more detail than in the Science paper cited in the lecture notes).

K. Fu, A. Knobloch, F. Martinez, D.C. Walther, C. Fernandez-Pello, A.P. Pisano, D. Liepmann, K. Miyaska and K. Maruta, "Design and Experimental Results of Small-Scale Rotary Engines," Proc. 2001 International Mechanical Engineering Congress and Exposition (IMECE), IMECE2001/MEMS-23924, New York, November 11-16, 2001. (Best published description of the Berkeley rotary engine work).

L. Merotto, C. Fanciulli, R. Dondè, S. De Iuliis, "Study of a thermoelectric generator based on a catalytic premixed meso-scale combustor," Applied Energy Vol. 162, pp. 346–353 (2016). Good paper on the development of catalytic-combustion drive thermoelectric power generation.

C. M. Spadaccini, J. Peck I. A. Waitz, "Catalytic Combustion Systems for Microscale Gas Turbine Engines," ASME Journal of Engineering for Gas Turbines and Power, Vol 29, pp. 49 – 60 (2007). (Paper on the MIT micro gas turbine project, emphasizing catalytic combustion aspects.)

S. E. Vargo, E. P. Muntz, G. R. Shiflett, W. C. Tang, "Knudsen compressor as a micro- and macroscale vacuum pump without moving parts or fluids," Journal of Vacuum Science and Technology A, Vol. 17, p. 2308 (1999). (Description of the Knudsen compressor experiments and modeling.)

Ha, S., Adams, B., Masel, R. I. (2004). "A miniature air breathing direct formic acid fuel cell," *J. Power Sources*, 128, 119-124. (Paper on the interesting UIUC work on formic acid fuel cells)

J. S. Wainright, R.F. Savinell,, C.C. Liu,, M. Litt (2003). "Microfabricated fuel cells," Electrochimica Acta 48, 2869-2877. (Paper describing CWRU's interesting micro PEM fuel cells)

Karagiannidis, S., Mantzaras, J., Jackson, G., Boulouchos, K., "Hetero-/homogeneous combustion and stability maps in methane-fueled catalytic microreactors," *Proc. Combust. Inst.* 31:3309-3317 (2007) (Excellent work on catalytic reactors with heat loss, wall heat conduction and gas-phase reaction.)

Menon, S., Moulton, N., Cadou, C., "Development of a Dynamometer for Measuring Small Internal-Combustion Engine Performance," *J. Propulsion Power* 23:194-202 (2007). Excellent paper on measuring the performance of very small internal combustion engines.

Part 2. The usual type of homework questions

1. You have just been hired as an Assistant Professor at UC Berkeley to replace Prof. Fernandez-Pello, who retired and moved to Bora Bora. You are trying to initiate a new project on the development of a 4-stroke single-cylinder piston engine running on propane fuel that provides **10 Watts** of electrical power. You can't utilize Prof. Pello's group's prior knowledge because his hard disk crashed and he never backed it up. His former graduate students and postdocs have all taken jobs in South Sudan and cannot be reached due to poor phone and internet service. Since you have taken AME 514 and are familiar with microscale combustion and power generation, your job is to figure out how to scale down an existing IC engine. (There's a lot of parts to this problem but breaking it up this way makes it easier to keep you on the intended path.)

a) Estimate the fuel flow (in kg/s) required assuming **5% conversion efficiency** of fuel to electricity.
b) Estimate the air+fuel flow (in both kg/s and m^3/s) assuming stoichiometric propane-air
c) If the propane-air mixture is compressed by a 10:1 volume ratio, what is the post-compression (but pre-combustion) pressure, temperature and thermal diffusivity? (Use GASEQ or a similar program).
d) Estimate S_L for this condition. Use the S_L correlations for propane at elevated T and P by Metghalchi and Keck (Combustion and Flame, Vol. 38, p. 143, 1980) which I have uploaded to the Lecture 6 papers folder.
e) Estimate the quenching distance = $40\alpha/S_L$ for this mixture.
f) Assume that the clearance height (distance from the top of the piston to the cylinder head) should be twice this distance to avoid quenching. The stroke (distance traveled by the piston) must be 9 times this distance to obtain a 10:1 volume compression ratio. What is the stroke?
g) Assuming bore (cylinder diameter) = stroke, what is the volume of the cylinder?
h) At what revolution rate must the engine rotate in order to obtain the required volume flow? (For a 4-stroke engine, the engine must complete two revolutions for each gulp of fuel-air mixture.)
i) Should you design the flow inside the cylinder to be laminar or turbulent? Do you have a choice? (What is the Reynolds number?)
j) By using the scaling analysis discussed in Lecture 4, estimate the importance of heat losses for this size of engine with this rotation speed and S_L.
k) By using the scaling analysis discussed in Lecture 4, estimate the importance of friction losses.

l) Estimate the importance of wall heat conduction (i.e. the ratio of gas-phase convection to wall conduction). Will the gas temperature increase significantly during compression?

m) Should this design using catalytic combustion instead of conventional (gas-phase) combustion? Why or why not? Use the Kaisare et al. model (Lecture 4) to estimate the heat release rate attainable from catalytic combustion; the spreadsheet used to generate the plots is at http://ronney.usc.edu/AME514/Lecture4/VlachosPropaneCatCombModel.xls.

n) If you found that the design was unfeasible due to friction or heat losses or heat transfer during compression, even after employing catalytic combustion, what is the minimum size of cylinder needed to avoid these problems?

(You'll probably want to use a spreadsheet or Matlab program to keep track of your calculations; hang on to it because we'll re-visit the problem after learning about turbulent combustion to see if combustion is fast enough under these conditions.)

2. After several years of work at Berkeley, you give up and decide to try some alternate power generation devices.

   a) Estimate the area of a single chamber solid oxide fuel cell (use Hibino's data under the most favorable condition) needed to produce 10 watts of electrical power. If you used this device in a "pizza" configuration (one disk exposed on both sides to ambient) and the heat loss coefficient to ambient were 10 W/m^2K, how much thermal power would be lost to ambient?

   b) Estimate the area of Bi_2Te_3 thermoelectrics that would be required to produce 10 Watts of electrical power assuming a hot-side temperature of 500K and cold-side temperature of 300K. The thermal conductivity of Bi_2Te_3 is about 2 W/mK and $ZT_a \approx 1$. Assume that you have massive fins attached to both the hot and cold side of the thermoelectrics that give you an effective heat transfer coefficient of 100 W/m^2K. Use the Δx for the thermoelectrics that maximizes the power (as explained in Lecture 6).

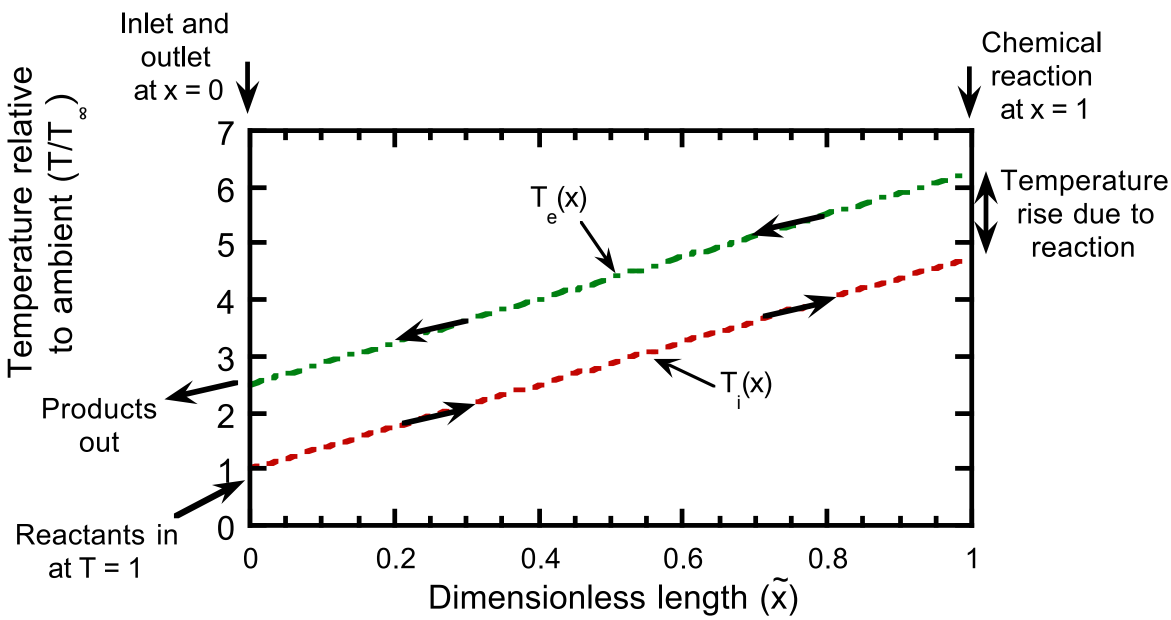
3. Using the formulas in the Lecture 6 notes, estimate the size (i.e. membrane area) and thermal power required for an aerogel-based thermal transpiration pump that will produce 0.1 N of thrust. Assume 300K inlet, 600K outlet, and a 1 mm thick membrane (meaning L = 1 mm / 10 = 100 μm, and use the most efficient operating condition, i.e. $\Delta P/\Delta P_{no\ flow} = 0.5$). The Knudsen number is 5. The thrust in this case is equal to the mass flow (=ρMcA, where ρ is the ambient air density, M the Mach number you calculated, c the sound speed, and A the area you're trying to find) multiplied by the exit velocity after expansion through a nozzle back to ambient pressure (in this case Bernoulli's equation will do, $u = (2\Delta P/\rho)^{1/2}$). (I've neglected a lot of temperature-averaging of properties and other things in these formulas, but that adds a lot of complexity for very little increase in knowledge gained…)

4. Using the equations in Lecture 4, show that the formula for the adiabatic, fast-reaction temperature $T_{reactor}$ of a heat-recirculating reactor (no heat loss so $h_2 = 0$, no wall conduction so $\tau = 0$, Da = ∞ so the temperature rise in the reactor = $T_e(L) - T_i(L)$ is just the adiabatic temperature rise $Y_{fuel}Q_R/C_P$) is as given in class

$$T_{reactor} = T_{adiabatic,\ no\ recirc} + \frac{h_1 L Y_{fuel} Q_R}{2\dot{m} C_P^2}$$

Note that $T_{adiabatic, no recirc}$ is just the usual adiabatic flame temperature = $T_\infty + Y_{fuel}Q_R/C_P$.

5. (From a previous years' final exam). Consider a linear counter-current heat exchanger and combustor as described in Lecture 4, slides 38 - 44. 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 41.) 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 (in some cases there may be no change). The inlet temperature $T_i(0) = 1$ is the same for every case. **Show in particular how the temperature at the reactor inlet $T_i(1)$, the temperature at the reactor outlet $T_e(1) = T_i(1)+\Delta T_C$ and the exhaust temperature $T_e(0)$ will change. 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)

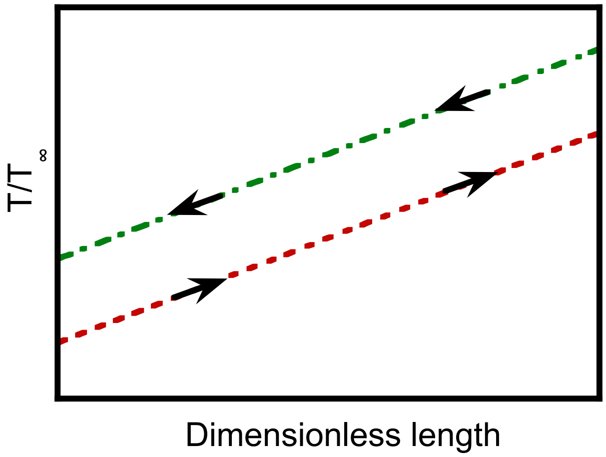
(b) The PDR® fuel additive of Problem 2 is used which decreases the fuel heating value by 10%

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

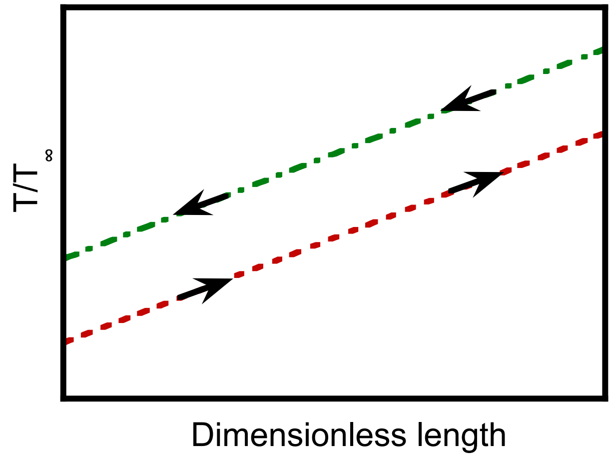
(d) The nitrogen in the air is replaced with a gas having a much lower thermal conductivity, but all other properties of the gas are the same as nitrogen

(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.

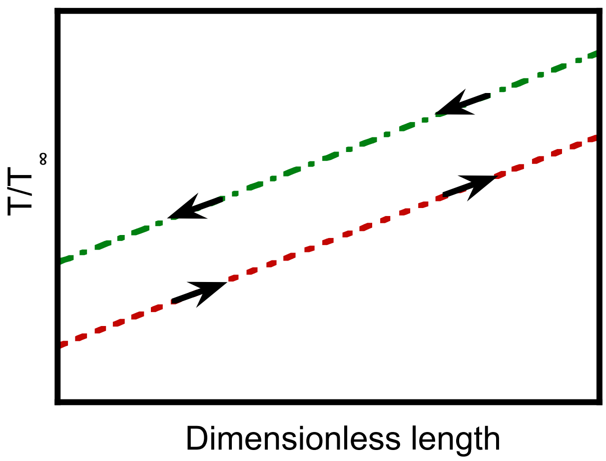
Problem #5.



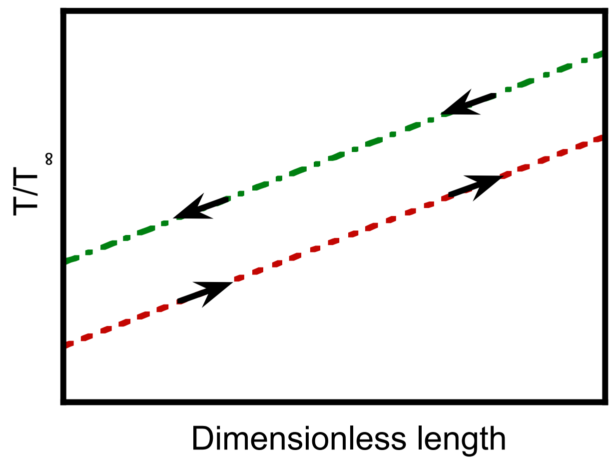
(a) *Planet X – 0.5x pressure*



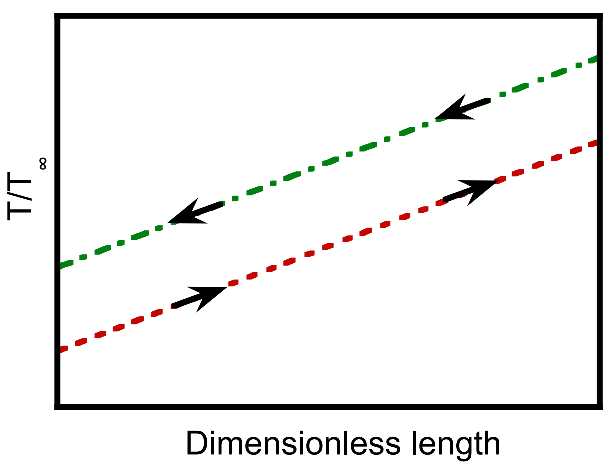
(b) *PDR® added – 10% decrease in* Q_R



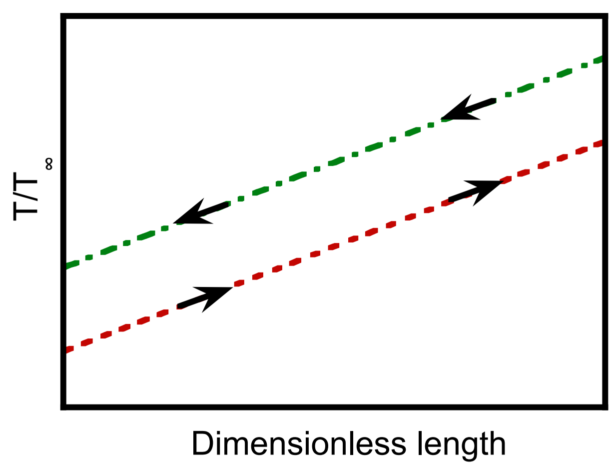
(c) Significant heat losses on reactant side only



(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!