

AME 514 Applications of Combustion - Fall 2008 – Homework #2

Due Wednesday 10/15/08, 4:30 pm, at my office (OHE 430J). If you're off campus, you can fax it to 213-740-8071. DEN students should submit through the usual channels. *Late homework marked down 10% per day.*

Part 1: paper review

Read any one of the research papers listed below (along with the reason I think they're important papers). Most of these papers are available on-line or in the Science and Engineering Library. *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.* As always, papers written by me are off limits. For your convenience, most of the papers are available on the class website in the /Lecture4/ folder (you're welcome...)

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

Jones, A.R., Lloyd, S. A., Weinberg, F. J., "Combustion in heat exchangers," Proc. Roy. Soc. Lond. A. 360:97-115 (1978). (Modeling of Swiss roll combustors).

Lloyd, S.A., Weinberg, F.J., Nature 251:47-49 (1974); Lloyd, S.A., Weinberg, F.J., Nature 257:367-370 (1975). (Key papers introducing the world to "Swiss roll" combustors. *Both papers are very short, treat the two papers as one.*)

Maruta, K., Muso, K., Takeda, K., Niioka, T., Proc. Combust. Inst. 28:2117-2123 (2000). (Good paper on flameless combustion).

Vican, J., Gajdeczko, B. F., Dryer, F. L., Milius, D. L., Aksay, I. A., Yetter, R. A., "Development of a Microreactor as a Thermal Source for MEMS Power generation," to appear in the Proceedings of the Combustion Institute, Vol. 29 (2002). (Best paper besides PDR's work on microscale Swiss roll combustion and power generation).

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. Miyasaka 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).

C. M. Spadaccini, J. Lee, S. Lukachko, I. Waitz, A. Mehra, X. Zhang, "High Power Density Silicon Combustion Systems for Micro Gas Turbine Engines," GT-2002-30082, Proceedings of ASME Turbo Expo, Amsterdam, The Netherlands, June 2002 (paper on the MIT micro gas turbine project, emphasizing the combustion aspects.)

Mehra, A., Zhang, X., Ayon, A., Waitz, I., and Schmidt, M., Spadaccini, C., "A 6-Wafer Combustion System for a Silicon Micro Gas Turbine Engine," Journal of Microelectromechanical Systems, Volume 9, Number 4, December 2000, pp.517-527

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 UIUC interesting 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)

J. D. Holladay, E. O. Jones, Ma Phelps, J. Hu (2002). "Microfuel processor for use in a miniature power supply", *Journal of Power Sources* 108, 21–27. (Paper describing PNNL's interesting micro-reformer for methanol).

Whalen, S., Thompson, M., Bahr, D., Richards, C., Richards, R. (2003). "Design, fabrication and testing of the P³ micro heat engine", *Sensors and Actuators A* 104, 290–298. (Description of the P³ engine work at Washington State.)

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.)

Prepare a critical review of the article, not to exceed 2 pages, structured as follows. PLEASE IDENTIFY EACH SECTION WITH A HEADING.

- 1) Why the author(s) conducted the work
- 2) Summary of the results
- 3) Summary of the conclusions
- 4) Your opinion of the merits of the work
- 5) Your opinion of the shortcomings of the work

Part 2. The usual type of homework questions

1. You have just been hired as a Professor at MIT to replace Prof. Epstein, who recently left to accept a high-ranking position in industry. You are trying to initiate a new project on the development of a micro gas turbine. You can't utilize Prof. Epstein'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 Iraq and cannot be reached due to poor phone and internet service. Prof. Epstein is a world-renowned expert on gas turbines but is not very familiar with combustion. 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 commercial gas turbine to a thrust of 0.1 Newton or 10 Watts of power if connected to an electrical generator. (This roughly corresponds to a mass flow of 0.0005 kg/s and an exit velocity of 200 m/s). This new design must use a conventional hydrocarbon fuel, not hydrogen. Also, unlike a conventional gas turbine, the micro turbine will be designed to operate at sea level and use a single stage compressor with a pressure ratio of 3 (i.e. the intake pressure is 1 atm and the post-compression pressure is 3 atm).

- a) Estimate the required compressor rotor diameter required to get the specified mass flow assuming the air goes through the compressor at $M = 1$. Assume that the compressor blade height is limited to 200 μm by the Deep Reactive Ion Etching fabrication technique. Furthermore, note that the velocity of the gas going through the compressor blades would be about the speed of sound, and assume that half of the flow path area is taken up by the blades themselves.
- b) Estimate the required compressor rotor speed (rev/min) to obtain $M = 1$.
- c) Estimate the required combustor volume. Use the stoichiometric burning velocity of hydrocarbons to calculate the chemical reaction time needed to estimate the combustor volume.
- d) By using the scaling analysis discussed in Lecture 4, Estimate the importance of heat losses compared to the macroscale (mega-scale?) engine. Choose any macroscale aircraft gas turbine engine as your baseline.
- e) Estimate the importance of wall heat conduction (i.e. the ratio of gas-phase convection to wall conduction) if a heat recirculating design is used (see lecture 6 notes, slide 56 for dimensions). The thermal conductivity of silicon is 150 W/mK (huge!).
- f) Should you design the flow inside the combustor be laminar or turbulent? Do you have a choice?
- g) Should this design use catalytic combustion instead of conventional (gas-phase) combustion? Explain why or why not. Use the lecture 4 notes to estimate the heat release rate attainable from catalytic combustion (ignore the fact that the Maruta et al. model used methane, not a higher hydrocarbon.)
- h) Estimate the viscous friction loss in the air bearings assuming the gap between the (spinning) shaft and the (stationary) bearing is 50 μm , the (axial) length of the bearing is 2 mm, and the shaft diameter is 2 mm. (Note that there has to be 2 such bearings). Use the revolution speed as estimated in part a.
- i) Is heat conduction along this shaft important if its length is 5 mm? (I know I said it was, see if the numbers support my claim).

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

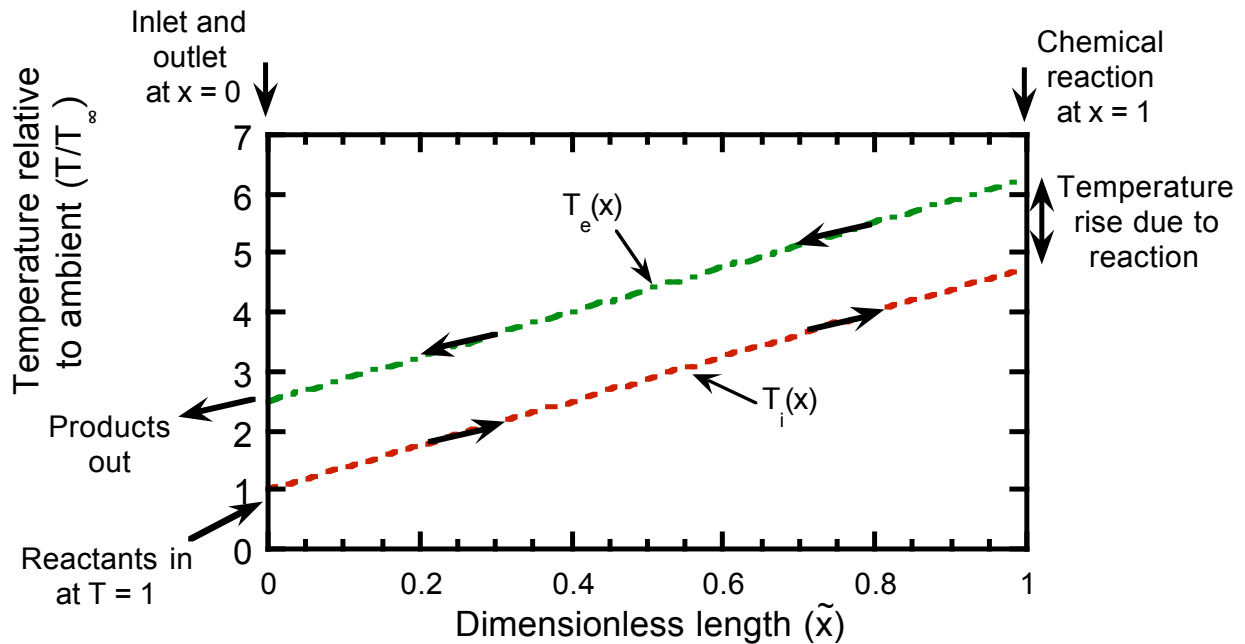
- a) Using the formulas on page 61 of the lecture 6 notes, estimate the size (i.e. membrane area) and thermal power required for an aerogel-based thermal transpiration pump that will produce 0.1 N of thrust. Assume 300K inlet, 600K outlet, and a 1 mm thick membrane (meaning $L = 1 \text{ mm} / 10 = 100 \text{ } \mu\text{m}$, and use the most efficient operating condition, i.e. $\Delta P / \Delta P_{\text{no flow}} = 0.5$). The Knudsen number is 5. The thrust in this case is equal to the mass flow ($= \rho M c A$, 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) (not the A defined on page 61) 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...)
- b) 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 $10 \text{ W/m}^2\text{K}$, how much thermal power would be lost to ambient?
- c) 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 $100 \text{ W/m}^2\text{K}$. Use the Δx for the thermoelectrics that maximizes the power (as explained in lecture 6, slides 9-10).

3. Using the equations on page 47, 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 $\tau = 0$, $\text{Da} = \infty$ so the temperature rise in the reactor $= T_e(L) - T_i(L)$ is just the adiabatic temperature rise $Y_{\text{fuel}} Q_R / C_p$) is as given in class:

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

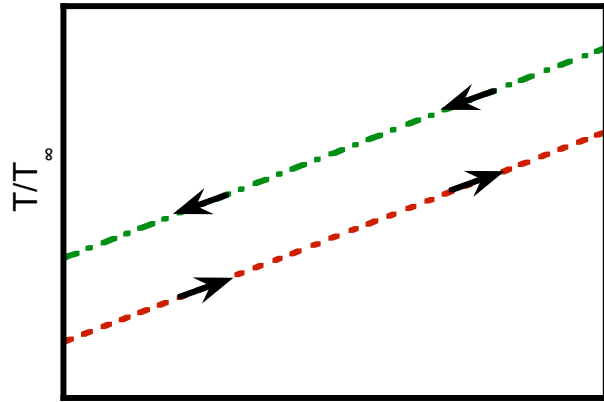
Note also that $T_{\text{adiabatic, no recirc}}$ is just the usual adiabatic flame temperature $= T_\infty + Y_{\text{fuel}} Q_R / C_p$.

4. (From last year's final exam). Consider a linear counter-current heat exchanger and combustor as described in Lecture 4, slides 43 - 51. 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 49.) Below is an expanded diagram just to help refresh your understanding about the meaning of this plot.



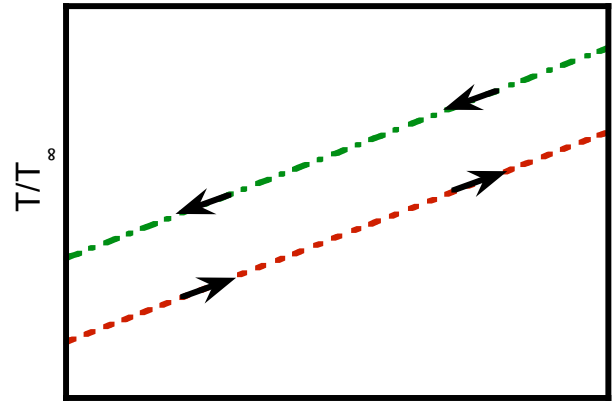
Show modified temperature profiles for each of the following modifications to this ideal combustor. Explain each answer in a few sentences.

- A different fuel with a much slower reaction rate is used, i.e. the reaction is close to extinction.
- The walls are roughened to make the flow turbulent in both the reactant and product streams.
- 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.
- 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).
- The mass flow rate is doubled (same mixture composition).



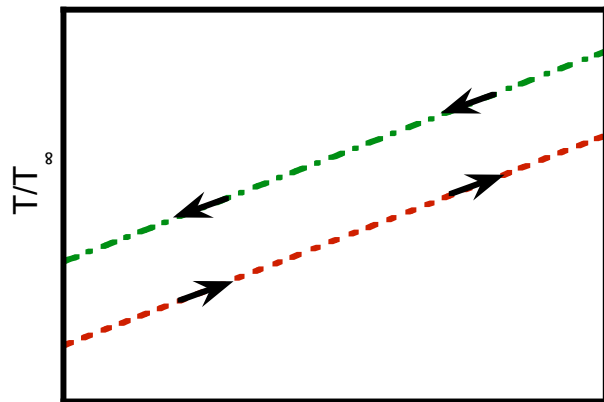
Dimensionless length

(a) A fuel with slower reaction rate is used



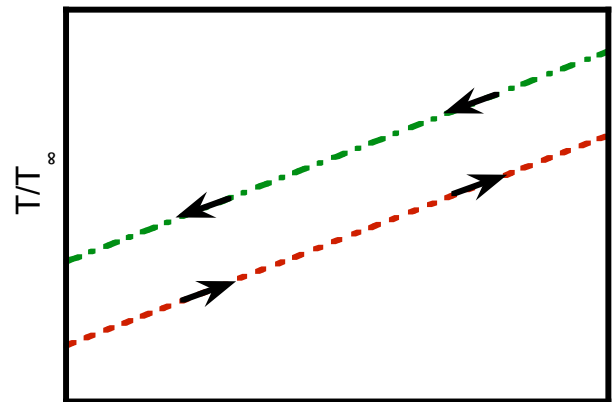
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(b) The walls are roughened - turbulent



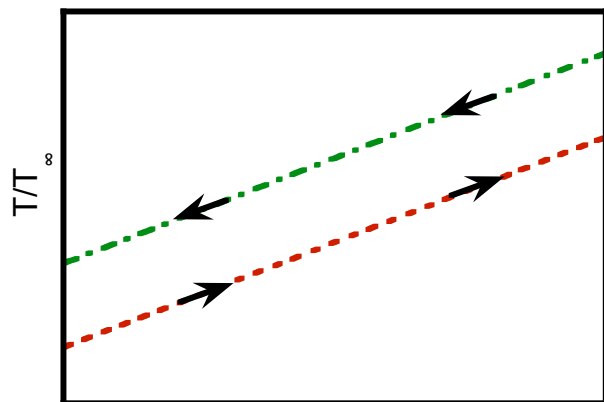
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(c) The dividing wall is non-conducting



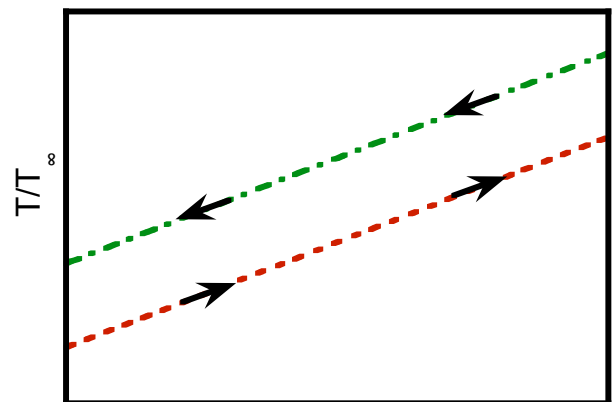
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(d) The walls are coated with a high- ϵ material



Dimensionless length

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



Dimensionless length

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