AME 514 Applications of Combustion - Fall 2008 – Homework #3

Due Wednesday 11/5/08, 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 of the research papers listed below. **For your convenience, most of the papers are available on the class website in the /Lecture7/ folder (you're welcome…)**

- Joulin, G., Sivashinsky, G. I. (1994). C*ombust. Sci. Technol.* 98, 11-23. Theoretical description of flames in Hele-Shaw cells. (If you want to review this one, I have a paper copy).
- Yoshida, A. (1988). *Proc. Combust. Inst.* 22, 1471-1478. Very good experimental characterization of distributed combustion. (If you want to review this one, I have a paper copy).
- Abdel-Gayed, R. G., Bradley, D. and Lung, F. K.-K. (1989) *Combust. Flame* 76, 213. Good experimental study and critical review of flame fragmentation quenching by turbulence.
- Cambray, P. and Joulin, G. (1992). *Twenty-Fourth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, p. 61. Very interesting theoretical/computational study of the effects of thermal expansion on premixed turbulent flame propagation. (If you want to review this one, I have a paper copy).
- Gouldin, F. C. (1987). *Combust. Flame* 68, 249. First paper on the fractal model of turbulent premixed flames.
- Poinsot, T., Veyante, D. and Candel, S. (1990). *Twenty-Third Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, p. 613. Interesting computational study of the role of heat loss on flame/vortex interactions and flame extinction. (If you want to review this one, I have a paper copy).
- H. Boughanem and A. Trouve (1998). *Proc. Combust. Inst.* 27, 971. Excellent computational study of the effects of thermal expansion and buoyancy on premixed turbulent flames.
- Buckmaster, J. D., *Combust. Sci. Tech.* 115, 41 (1996). First theoretical description of edge flames. (If you want to review this one, I have a paper copy).
- Buckmaster, J. D. and Short, M. (1999). Cellular instabilities, sub-limit structures and edge-flames in premixed counterflows. *Combust. Theory Modelling* 3, 199-214. First paper describing in detail the flame tube phenomenon.
- M. S. Cha and S. H. Chung (1996). Characteristics of lifted flames in nonpremixed turbulent confined jets. *Proc. Combust. Inst.* 26, 121–128. Very good experimental paper on lifted nonpremixed flames.
- J. Daou, A Liñán (1998). "The role of unequal diffusivities in ignition and extinction fronts in strained mixing layers," *Combust. Theory Modelling* 2, 449–477. Very good theoretical/computational paper on the propagation rates of nonpremixed edge flames including Lewis number effects.

- J. Daou and A. Liñán (1999). "Ignition and extinction fronts in counterflowing premixed reactive gases," *Combust. Flame.* 118, 479-488. Very good theoretical/computational paper on the propagation rates of premixed edge flames including Lewis number effects.
- R. W. Thatcher and J. W. Dold (2000). "Edges of flames that do not exist: flame-edge dynamics in a non-premixed counterflow." *Combust. Theory Modelling* 4, 435-457. Good theoretical/computational paper on "flame tube" formation in nonpremixed flames.
- R. Daou, J. Daou, J. Dold (2002). "Effect of volumetric heat-loss on triple flame propagation" *Proc. Combust. Inst.*, Vol. 29, pp. 1559 - 1564. Definitive theoretical paper on the effect of heat loss on nonpremixed edge flames.
- Ruetsch, G. R., Vervisch, L. and Linan, A. (1995). Effects of heat release on triple flames. *Physics of Fluids* 7, 1447. First study of the effects of thermal expansion on edge-flame speeds.

Prepare a critical review of the article, not to exceed 2 pages, structured as follows:

- Why the author(s) conducted the work
- Summary of the results
- Summary of the conclusions
- Your opinion of the merits of the work
- Your opinion of the shortcomings of the work

Part 2. The usual type of homework questions

1. By analogy with the analysis for laminar flames in tubes, develop a criterion for the extinguishment, via heat losses to tube walls, of turbulent flames in the distributed reaction zone regime. Assume the integral scale is equal to the tube diameter (not a bad assumption!) Compare with Bradley's (older) quenching criteria $Ka \approx 0.08\ Re_L^{1/2}$ for $Re_L < 300$, and $Ka \approx 1.6$ = constant for $Re_L > 300$.

2. Redo the analysis of lifted flames for a very long **slot jet** instead of a round jet. The only difference in the analysis is that the area is proportional to $r_{jet}L$, where L is the (constant) length of the slot in the long dimension, rather than r_{jet}^2. In particular
   a) compute the scaling of mean velocity, jet width and mass flux as a function of the axial distance x.
   b) compute the scaling of mean strain rate as a function of jet Reynolds number
   c) compute the expected scaling of liftoff height as a function of jet Reynolds number

3. In class it was suggested that the liftoff height (x_{LO}) of a nonpremixed round jet flame is at the location where the mean turbulent strain rate is equal to the extinction stretch rate of a laminar flame (Σ_{ext}). Several other mechanisms of stabilization of turbulent lifted jet flames have been proposed. Determine the scaling relationship between liftoff height (x_{LO}) and the jet parameters exit velocity (U_o), jet exit diameter (d_o), gas viscosity (ν) and flame parameters S_L and/or Σ_{ext} assuming the lifted flame is located at the position where
   a) the transition from flamelet to distributed combustion occurs, i.e., Ka = 1
   b) the mean velocity ($\overline{u}$) is equal to the turbulent burning velocity (S_T) of a distributed flame with burning velocity given by Damköhler's model

c) the mean velocity ($\bar{u}$) is equal to propagation speed of a non-premixed edge flame (actually, a bunch of edge flames) propagating with an edge speed given by Daou and Liñan's model
d) the mean velocity ($\bar{u}$) is equal to the turbulent burning velocity (S_T) of a wrinkled laminar flame with burning velocity given by Gouldin's fractal model assuming the Kolmogorov scale, L_K, is the inner cutoff scale.
e) the mean velocity ($\bar{u}$) is equal to the turbulent burning velocity (S_T) of a wrinkled laminar flame with burning velocity given by the "standard" flamelet relation $S_T \sim u'$ (why doesn't this one work???)

For your convenience, here are the turbulent round-jet scaling relations:

$$Q = \rho \bar{u}^2 r_{jet}^2 = \text{constant},\ r_{jet} \sim x \Rightarrow \bar{u} \sim U_o d_o / x \qquad \dot{m} \sim (\rho Q)^{1/2} x \sim \rho U_o d x$$

$$\mathrm{Re}_L = \frac{u' L_I}{\nu} \sim \frac{U_o d_o}{\nu} = \mathrm{Re}_{d_o} = \text{constant} \qquad \text{Mean strain} \sim \mathrm{Re}_{d_o}^{3/2} \frac{\nu}{x^2}$$

4. Edge flames
   a) For a nonpremixed methane-air edge flame with $\beta \approx 15$, $Le \approx 0.8$, approximately what strain rate (Σ) would correspond to zero edge speed? Use Daou and Liñán's model and estimate all necessary parameters needed to obtain a dimensional value of Σ (in 1/sec) from their dimensionless parameters.
   b) For this same case, approximately what strain rate (Σ) would correspond to the maximum edge speed? What would this maximum speed be (in cm/sec)?
   c) For this same case, how much higher would this maximum speed be if thermal expansion effects were included?

5. 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 $Ka = 0.37\, \mathrm{Re}_L^{1/2}$?
   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.)