AME 514 Applications of Combustion – Spring 2017

Assignment #3

Due Friday 4/14/17, 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 of the research papers listed below. **For your convenience, most of the papers are available on the class website in the /LectureN/ folder, where N = 7, 8 or 9**

- Joulin, G., Sivashinsky, G. I. (1994). *Combust. Sci. Technol.* 98, 11-23. Theoretical description of flames in Hele-Shaw cells.
- Yoshida, A. (1988). *Proc. Combust. Inst.* 22, 1471-1478. Very good early experimental characterization of distributed combustion.
- 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.
- 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. Good paper on flame-vortex interaction, although it has a weakness – can you identify it?
- H. Boughanem and A. Trouve (1998). The domain of influence of flame instabilities in turbulent premixed combustion. *Proc. Combust. Inst.* 27, 971. Excellent computational study of the effects of thermal expansion and buoyancy on premixed turbulent flames.
- 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.
- Kalghatgi, G. T. (1984). Lift-Off Heights and Visible Lengths of Vertical Turbulent Jet Diffusion Flames in Still Air. *Combust. Sci. Tech.* 41, 17-29. Excellent early paper on lifted nonpremixed turbulent jet flames.
- N. I. Kim, J. I. Seo, Y. T. Guahk and H. D. Shin (2006). "The propagation of tribrachial flames in a confined channel," *Combustion and Flame*, Vol. 146, pp. 168 - 179. One of the best experimental papers on triple 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.

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 – what did they intend to do that was **new** at the time?
2) Summary of the methods used (is the work experimental, computational, analytical or some combination?)
3) Summary of the most important results
4) Summary of the conclusions – this is not just a restatement of the results, but how the authors **interpreted** the results to create a **new piece of knowledge** that didn't exist before the work was done.
5) Your opinion of the merits of the work
6) Your opinion of the shortcomings of the work
7) **ONE sentence** summary of the **most important message** the authors were trying to convey. Again this is not a restatement of the results but a summary of the new knowledge created by the work.

Follow the suggestions for writing your review as given in Homework #1.

Part 2. The usual type of homework questions

1. By analogy with the analysis for laminar flames in tubes, namely Pe = 40 at the extinction limit, 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 half of 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 ($\overline{u}$) 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???)
f) The same as (b), but with the lifted flame not stabilized on the jet axis. In this case you'll need to find both the liftoff height x_{LO} as before and the radius (distance from jet centerline) r_{LO} where this occurs. In order to do this, you'll need to make an assumption about how $\bar{u}$ and the fuel mass fraction Y vary with x and r according to

$$\bar{u}(x,r) \sim U_o \frac{d_o}{x} \exp\left[-\left(\frac{r}{x}\right)^2\right]; Y(x,r) \sim Y_\infty \frac{d_o}{x} \exp\left[-\left(\frac{r}{x}\right)^2\right]$$

i.e., a Gaussian profile whose centerline behavior is the same as part (b) but whose width increases linearly with downstream distance. Since there are two unknowns, you'll need two stabilization criteria: $\bar{u}(x,r) = S_T$ as before with part (b), plus $Y(x,r) = Y_s$, where Y_s is the stoichiometric fuel mass fraction. (Typically $Y_\infty = 1$, i.e. pure fuel at the jet exit).

4. Edge flames
   a) For a nonpremixed methane-air edge flame with non-dimensional activation energy $\beta \approx 15$, Lewis number Le ≈ 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. 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)