

AME 436	Assigned: Wednesday 2/7/2018
Problem Set #2	<ul style="list-style-type: none"> <li>• Due Wednesday 2/14/2018 at 4:30 pm in drop-off box in OHE 430N (back room of the OHE 430 suite of offices, where the Xerox machine is located)</li> <li>• Hard copies are preferred but you can email your assignment to the graders at <a href="mailto:ame436usc@gmail.com">ame436usc@gmail.com</a> if you're off campus. <b>Emailed files must be a single .pdf file, not 10 or 20 .jpg images!</b></li> <li>• DEN students submit through the usual channels.</li> </ul>

**Problem #1 (10 points) (Continuation of the problem from Homework #1)**

On Titan, one of Jupiter's moons, is an atmosphere of pure  $C_3H_8$  at 0.2 MPa (2 earth atmospheres) pressure at a temperature of 240K. Deep underground are deposits of 40 mole percent  $O_2$  and 60 mole percent  $N_2$  that the Titans pump out of the ground. Unfortunately, most of the  $O_2/N_2$  wells are located in politically unstable regions of Titan, so this  $O_2/N_2$  mixture is a valuable resource which they call "fuel." The propane in the atmosphere, which they call "air," is "free" as far as Titans are concerned.

- (e) Relative to flames on earth, do stoichiometric **premixed** flames on Titan produce more or less CO emissions due to incomplete combustion? Explain why – no credit without explanation.
- (f) Relative to flames on earth, do **nonpremixed** flames on Titan produce more or less soot? Explain why – no credit without explanation.

**Problem #2 (15 points) (Continuation of the problem from Homework #1)**

On Planet X (which is completely unrelated to Titan), the atmospheric pressure is exactly half that of earth's atmosphere. All other properties of the atmosphere, specifically the ambient air temperature ( $T_\infty$ ), composition ( $O_2 + 3.77 N_2$ ), thermal conductivity ( $k$ ), heat capacities ( $C_p$ ,  $C_v$ ) are exactly the same as on earth. How would each of the following properties be different on Planet X than on earth? In particular, state whether the property increase or decrease and by a factor of less than, more than, or exactly a factor of 2. In some cases there may be no change at all. **No credit without explanation.**

- d) Laminar burning velocity of a stoichiometric methane-air mixture
- e) Turbulent burning velocity of a stoichiometric methane-air mixture (assume  $u'$  same on earth as on Planet X)
- f) Time for homogeneous explosion in a stoichiometric methane-air mixture
- g) Length of a nonpremixed laminar gas-jet flame
- h) Length of a nonpremixed turbulent gas-jet flame
- i) Rate of thermal NO formation immediately behind a stoichiometric premixed methane-air flame
- j) Concentration of NO far downstream of a stoichiometric premixed methane-air flame, i.e. at equilibrium, assuming perfectly adiabatic conditions

### **Problem #3 (15 points)**

Using the Zeldovich equation for burning velocity ( $S_L$ ), and typical “baseline” values of ambient temperature ( $T_\infty$ ), adiabatic flame temperature ( $T_{ad}$ ), order of reaction ( $n$ ) and activation energy ( $E$ ), answer the following questions:

- How does the reactant temperature  $T_\infty$  affect  $S_L$ , everything else (including the product temperature  $T_{ad}$ ) held constant? That is, will a 10% increase in  $T_\infty$  cause a more or less than 10% increase/decrease in  $S_L$ ?
- How does adiabatic flame temperature  $T_{ad}$  affect  $S_L$ , everything else (including  $T_\infty$ ) held constant? That is, will a 10% increase in  $T_{ad}$  cause a more or less than 10% increase/decrease in  $S_L$ ?
- How does the concentration of fuel in the reactants affect  $S_L$ , everything else (including  $T_\infty$  and  $T_{ad}$ ) held constant? That is, will a 10% increase in the concentration of fuel in the reactants cause a more or less than 10% increase/decrease in  $S_L$ ?
- How does the pressure of the reactants affect  $S_L$ ? That is, will a 10% increase in pressure cause a more or less than 10% increase/decrease in  $S_L$ ?

### **Problem #4 (20 points)**

For the homogeneous reaction/ignition problem discussed in class, and taking into account the definitions of the dimensionless input parameters  $\phi$ ,  $\beta$  and  $H$  in the equation on page 35 of the Lecture 4 notes, answer the following questions about homogeneous ignition. You can use the simple Excel sheet (<http://ronney.usc.edu/AME436/autoignition.xls>) (also embedded in that Lecture 4 slide) I created or you build your own program in Excel, Matlab, wolframalpha.com, etc.)

- How does the reactant temperature  $T_\infty$  affect the **dimensional** time for ignition to occur (arbitrarily defined as 90% completion of reaction), everything else (including the product temperature  $T_{ad}$ ) held constant? That is, will a 10% increase in  $T_\infty$  cause a more or less than 10% increase/decrease in the dimensional time for ignition to occur?
- How does  $T_{ad}$  affect the **dimensional** time for ignition to occur, everything else (including  $T_\infty$ ) held constant?
- How does the concentration of fuel in the reactants affect the **dimensional** time for ignition to occur?
- How does the pressure of the reactants affect the **dimensional** time for ignition to occur?

### **Problem #5 (20 points)**

- Calculate and plot the homogeneous ignition time at constant pressure as a function of initial temperature for a stoichiometric ( $\phi = 1$ )  $C_3H_8$  - air mixture at 1 atm over the initial temperature range 1000K - 2000K using the on-line chemical kinetics calculator at

<http://navier.engr.colostate.edu/code/code-5/index.html>.

Use for 1000K the following parameters: integration time 1 seconds, time interval 0.05 seconds, MethaneOxygenNitrogen mechanism (note that the “MethaneOxygenNitrogen” mechanism includes many other hydrocarbon molecules including  $C_3H_8$ ). For higher initial temperatures the time to ignition will decrease and you should decrease the integration time. Note that if you

click on the question marks you'll find out what the calculation parameters mean:

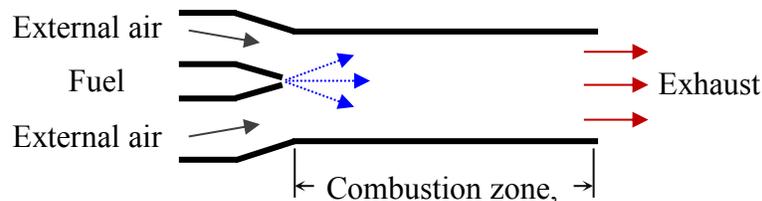
- **Integration time:** The integration proceeds from time zero until this final time.
- **Time interval:** The time interval for solution printouts to the text output file.
- **Ignition time:** For calculations at constant pressure or constant volume, the program computes an ignition time, which is denoted as the time when the temperature first reaches a value equal to the specified ignition temperature. The default value for this quantity is the initial temperature plus 400 K.

(None of these three calculation parameters have any effect on the calculation itself, just how the data is presented.)

- b) From this information, estimate the effective activation energy of  $C_3H_8$  - air combustion from a plot of  $\ln(\text{ignition time})$  vs.  $1/T_\infty$  (the slope of this plot is  $E/R$ ). (Note: the slope may not be very constant due to change in the dominant chemical reactions above a certain temperature. If this happens, determine separately the effective activation energies for these two regions, above and below the kink.)
- c) Calculate and plot the ignition time at constant pressure as a function of pressure for a stoichiometric  $C_3H_8$  - air mixture at 1000K over the pressure range 1 atm - 10 atm using the on-line chemical kinetics calculator.
- d) From this information, estimate the effective order of reaction ( $n$ ) of  $C_3H_8$  - air combustion from a plot of ignition time vs. pressure (the slope of this plot on a log-log scale is  $1-n$ )
- e) For initial temperature 1000K and pressure 1 atm, how different is the ignition time change for  $\phi = 0.5$  or  $\phi = 2$  compared to  $\phi = 1$ ?
- f) For initial temperature 1000K, pressure 1 atm and  $\phi = 1$ , how different is the ignition time for  $H_2$  - air and  $CH_4$  - air mixtures compared to the  $C_3H_8$ -air mixture?

**Problem #6 (20 points) (problem written by Jakarapop – thanks!)**

A cylindrical combustor has to be designed to fit within the limited space of a small airbreathing engine. The combustor uses air pressurized air with liquid fuel injected as droplets into the combustor at high velocity compared to the air velocity as shown in the figure below.



The combustor properties are estimated as follows:

- Air specific heat capacity ( $C_p$ )                      1400 J/kg
- Air thermal conductivity ( $k$ )                      0.024 W/mK
- Inlet air temperature ( $T_\infty$ )                      330 K
- Fuel latent heat of vaporization ( $L_v$ )              270 kJ/kg

- Fuel boiling temperature ( $T_d$ )                      349 K
- Fuel heating value ( $Q_R$ )                              43 MJ/kg
- Fuel density ( $\rho_d$ )                                      840 kg/m<sup>3</sup>
- Fuel-to-air mass ratio (FAR)                        0.065
- Average fuel droplet diameter ( $d(0)$ )            100  $\mu\text{m}$  ( $1 \mu\text{m} = 10^{-6} \text{m}$ )
- Average fuel droplet velocity ( $u$ )                160 m/s
- Gas viscosity ( $\nu$ )                                      0.2 cm<sup>2</sup>/s

- a) What is Reynolds number of the droplet?
- b) What is the droplet burning rate constant ( $K$ )?
- c) What is the droplet burning time?
- d) What is the shortest possible length of the combustion zone? (That is, given the droplet velocity  $u$  and the droplet burning time  $t$ , what is  $u \cdot t$ ?)
- e) Because of limited space, some possible methods to minimize the length of the combustor have been suggested:
  - i. Preheat the air to 700K using heat from the exhaust gas
  - ii. Use additives to decrease the fuel activation energy by 25%
  - iii. Increase the fuel pump pressure and decrease the nozzle orifice diameter to decrease the droplet diameter by 25%
  - iv. Use “oxy-fuel combustion”, which means supplying pure oxygen to the combustor instead of air (fuel flow rate unchanged), which increases FAR to 0.285

Which of these modifications would result in the shortest possible combustor length?