Homework #2: Deflagrations/Laminar Premixed Flames

1. Premixed Flame Quenching (part c is a former midterm problem)
   Assume the quenching diameter for a stoichiometric mixture of propane and air at STP in a cylindrical metal tube is 2.0 mm.
   a) If we had a stoichiometric mixture of propane and air at 2 atm and 500 K, would you expect a flame to be able to propagate through a 2 mm metal tube filled with our mixture?
   b) If we had a stoichiometric mixture of propane and air at STP in a 2 mm ceramic tube, would you expect a flame to be able to propagate through the tube?
   c) If the air was replaced with pure O₂, would you expect a flame to be able to propagate through the 2.0 mm diameter metal tube.
   c) If we could “magically” increase the mass diffusivity (D) of this mixture without changing its thermal diffusivity (α), would you expect a flame to be able to propagate through a 2 mm metal tube? (Be sure to explain your answer; and make sure you consider the influence of changing D on all aspects of the mechanisms that control flame propagation).

2. Mass Burning Rate
   In many situations, rather than concerning ourselves with the propagation speed of a flame, we prefer to examine the rate at which a flame can consume reactants on a mass basis, typically called the mass burning rate. For example, the heat release rate from the flame can be related to the mass burning rate and the heating value of the fuel. For a 1-d flame, the mass burning rate is typically defined as a mass flux, i.e., ρu (kg/m²s), since a simple increase in flame area will result in a greater mass consumption rate.
   a) Find an expression for the pressure dependence of the mass burning rate of an unstretched, adiabatic, laminar flame, based on the two-zone, single-step global reaction rate model used to create the S₁ expression developed in class.
   b) Estimate how much the mass burning rate would change for a room temperature, methane-air mixture as pressure was increased from 2 to 20 atm.

3. Flame Stretch (part of a former midterm problem)
   Consider two reactant mixtures: 1) H₂/O₂/Ar and 2) H₂/O₂/He. The mole fraction of Ar in mixture 1 is the same as the mole fraction of He in mixture 2. For an equivalence ratio of 0.7 and an Ar (or He) mole fraction of 80%, which mixture will have a stronger relative sensitivity to flame stretch, i.e., ∂(S₁₀/Σ₀)/∂κ. Indicate your answer below and EXPLAIN why.
4. **Flammability Limits** (former midterm problem)

The following table gives measured flammability limits (at 1 bar and 300 K) for four fuel/oxidizer combinations. The limits are given in terms of mole fraction of fuel in the reactants.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Oxidizer=Air</th>
<th></th>
<th>Oxidizer=O₂</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lean Limit</td>
<td>Rich Limit</td>
<td>Lean Limit</td>
<td>Rich Limit</td>
</tr>
<tr>
<td>H₂</td>
<td>4%</td>
<td>75%</td>
<td>4%</td>
<td>94%</td>
</tr>
<tr>
<td>CH₄</td>
<td>5%</td>
<td>15%</td>
<td>5%</td>
<td>61%</td>
</tr>
</tbody>
</table>

a) For each of the fuels, the lean flammability limits (in terms of fuel mole fraction) are independent of the oxidizer type. Explain.

b) Explain the change in rich limits when the oxidizer is switched from air to oxygen.

c) In terms of equivalence ratio (rather than fuel mole fraction), which oxidizer (O₂ or air) has a “leaner” lean flammability limit? Note, you do not need to calculate the actual equivalence ratios; a short explanation is also acceptable.

5. **Bunsen Burner Flame Stability**

In class, we noted that a quasi-one-dimensional flame will remain stationary (i.e., fixed in space relative to a burner or combustor) if the local flame speed, which we will denote as \( u_f \), here, is equal to the local gas velocity normal to the flame.

a) Write an expression which describes the local flame angle (\( \phi \)), relative to the direction of the incoming flow, in terms of \( u_f \) and the local gas velocity \( u_g \). Draw a picture to help define your angle \( \phi \).

b) Assuming a uniform gas mixture with a non-uniform flow velocity exiting a tube (the left half is shown below), sketch the shape of the flame zone for a stationary flame that does not enter the tube. Also sketch the profile of the local flame speed across the tube that would correspond to your flame zone choice. Assume the flame **is not lifted**, but do not assume a flame speed profile that exactly matches the velocity profile. **Draw all your sketches on a single figure that is a copy of the one below.**
c) Now consider the case of a lifted flame. Shown below is a magnified view of the region near the edge of the burner. The gas velocity profile (at the height above the tube exit as indicated by the dashed line) is shown as $u_g$.

First, on a copy of this figure, draw a profile of the local flame speed (at the same height) that would correspond to a stationary flame which would pass through the point A, but not exist at any lower position (i.e., no closer to the exit plane of the burner).

Assume that the sketch you have just drawn is the flame speed for a stoichiometric fuel/air mixture exiting the tube into a surrounding gas consisting of nitrogen (Case 1). Keeping the gas exit velocity the same as above, consider two new cases: Case 2) a fuel rich mixture (near but within the flammability limit) exiting into nitrogen and Case 3) the same fuel rich mixture exiting into air. On the same diagram, now draw $u_f$ profiles (corresponding to the same height above the tube as the $u_g$ shown) for these two cases. Make sure to label each of your flame speed profiles.

\[ u_g, u_f \]

\[ A \]

\[ \text{d) On a copy of the figure below, draw the flame front location for each of the above cases (again be sure to identify each of the three cases).} \]

\[ \text{e) For which case will blowoff occur first as we increase the velocity of the gases exiting the burner tube.} \]
**EXTRA CREDIT: Flame Length** (former midterm problem)

A premixed, stoichiometric propane/air laminar flame is stabilized on top of a two-dimensional slot burner as shown in the sketch below. The width of the burner (distance between the two walls of the slot) is $W$. The flame length (or the flame height at the middle of the burner) is $L_f$, and the burner exit velocity and temperature are $u_e$ and $T_e$. For this mixture, with $W=1$ cm, $u_e=2$ m/s, and a pressure of 1 atm, the flame length is 4 cm.

(a) What would $L_f$ be if we doubled the exit velocity to 4 m/s. You may assume the other operating conditions remain the same, and that the flame remains anchored at the burner exit.

(b) What would $L_f$ be if we operated the system at a pressure to 5 atm but *used the same reactant mass flow rate through the burner as in the original case*. You may assume the exit temperature remains unchanged, the flame remains anchored at the burner exit, and the global propane-air reaction rate has an order of 1.7.