MCL 343 Introduction to Combustion
Major Test (28 Marks, 4 Problems, 2 Hours)

6.5.2017

1. In an experiment to determine the laminar burning velocity using a constant-volume, pancake shaped combustion bomb, the instantaneous radius of the flame, $R_F(t)$, and the temperature in the unburned mixture ahead of the flame, $T_u(t)$, are measured simultaneously. No other measurements are made. The mixture is ignited using a spark located at the center of bomb. The flame is assumed to be perfectly circular as it propagates outwards. It can be assumed that the products behind the flame front remain stationary, while the reactants ahead of the flame move towards the outer wall of the chamber. The sidewalls of the bomb are conductive and **allow heat transfer from the combustion products** during flame propagation. It is also known that the temperature of the products behind the flame is not uniform due to the change of the reactants' state with time and also due to energy loss by heat transfer.

   The following parameters are given:
   - The diameter D_o and width W_o of the bomb.
   - The equivalence ratio of the methane-air mixture used to fill the bomb φ.
   - The enthalpy of reaction of methane per unit mass of methane $\Delta h_{R,f}$.
   - The initial pressure p_o and temperature T_o of the mixture.

   $\Delta h_{R,f}(\rho_F(t)) = c_p($

   Furthermore, we assume that:

   - The specific gas constants R_g (J/kg-K) and the specific heats of the reactants and products c_p (J/kg-K) are the same and remain constant during the flame propagation, and
   - The energy loss from the **reactants** and from the **flame** itself is **negligible**.

We want to use the measurements to calculate the laminar burning velocity over the range of pressures and temperatures experienced by the reactants during the flame propagation.

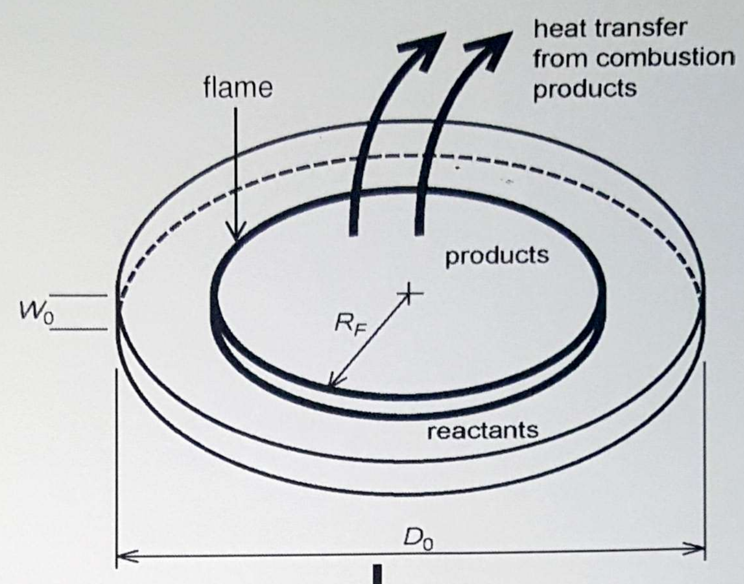
In terms of the above given parameters including $R_F(t)$ and $T_u(t)$, derive expressions for the following quantities as function of time:

1. The reactants pressure p_u.
2. The burned gas temperature T_F and density ρ_F **immediately** behind the flame.
3. The laminar burning velocity S_u measured with respect to the reactants.
4. The mass burned m_b.
5. The average temperature of the products T_p.
6. The total energy lost via heat transfer Q_l. **12 marks**

$c_p - c_v = R$

$c_v = c_p - R$

$\gamma = \frac{c_p - R + R}{c_p - R}$ $\frac{R}{}$



Schematic illustration

2. A fluid flow with uniform mass flux is established between points A and B along the x-direction as shown in fig. 2. The temperature in the region A-B varies from T_A to T_B ($T_A > T_B$).

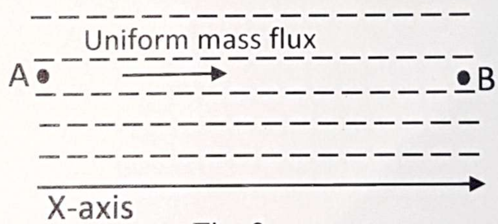


Fig. 2

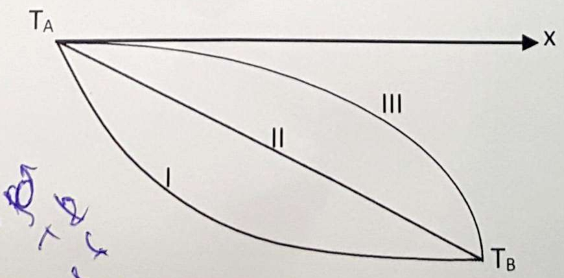
There is no flow, heat transfer, or any other variations in the y, z directions. Argue which of I, II, III is likely to be the shape of the temperature profile in region A-B. You may either use simple control volume arguments or use the 1-D energy equation.

5 marks

$$\rho V_x c_P \frac{dT}{dx} = \lambda \frac{d^2T}{dx^2}$$

$p = \rho RT$

$\frac{d^2T}{dx^2} = k\frac{dT}{dx}$



$\frac{dT}{dx} = e^{kx}$

$\frac{d}{dx}\left(\frac{dT}{dx}\right) = k\frac{dT}{dx}$

$\ln\left(\frac{dT}{dx}\right) = kx + c_1$

$\frac{dT}{dx} = e^{kx+c_1}$

$T = \frac{1}{k}e^{kx+c_1}$

$\dot{Q} = -kA\frac{dT}{dx}$ $\frac{J}{s} = k$

3. Assume n≈2 (order of reaction). Then the quenching distance $d = \sqrt{2b}\,\Delta_F \propto \frac{\alpha}{S_u}$

   not i is proportional to the laminar burning velocity

   ii is proportional to the flame thickness

   iii increases with temperature

   iv increases with pressure

   v is minimum at the stoichiometric equivalence ratio and increases for lean/rich mixtures.

   Reason: $S_u = \sqrt{\frac{\alpha}{S_u}\frac{\dot{w}_{i,f}}{Y_{f,u}}}$ **3 marks**

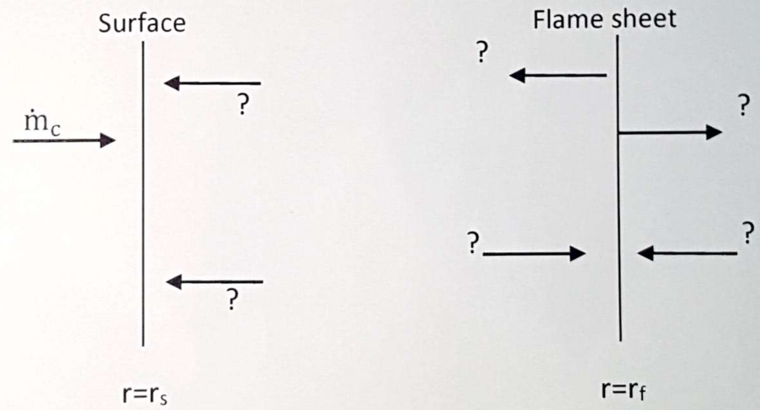
4. Consider the two-film burning of a coal particle. Carbon reacts with CO_2 at the particle surface producing CO, which burns with O_2 at the flame sheet. The reaction at the carbon particle surface is

$$C + CO_2 \longrightarrow 2CO$$

The reaction at the flame sheet is:

$$CO + 0.5\,O_2 \longrightarrow CO_2$$

   A. Assuming that $\dot{m}_c$ (kg/s) is the burning rate of carbon at the surface, determine the mass flow rates of CO_2, O_2, CO at the carbon surface and at the flame sheet in terms of $\dot{m}_c$.



   Also draw the directions of the flowrates of the individual species on the diagrams above. **4 marks**

   B. Draw the temperature and species profiles ($Y_{CO_2}, Y_{O_2}, Y_{CO}$) for the two film burning case in the diagram as shown **4 marks**