- **This exam carries a total of 13 questions on 2 pages for a total of 60 points.**
- **All questions must be answered.**
- **Make suitable assumptions where necessary while solving these questions, and justify them appropriately.**
- **This exam is open notes, open book and due by May 16th, 11:59 PM.**

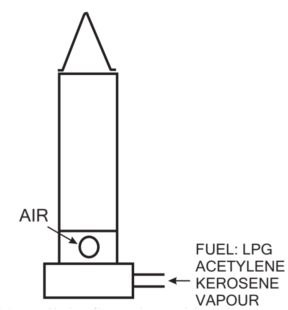
1. (5 points) A counterflow burner with circular nozzles issues a lean methane/air mixture with $\phi = 0.6$ from the left nozzle flowing against a rich methane/air mixture with $\phi = 1.5$ from the right nozzle. As easily seen, a planar lean premixed flame and a planar rich premixed flame will be established in the flow field between the two nozzles, which are perpendicular to the axial direction. Flammability limits of methane-air mixtures are $\phi = 0.5$ (LFL) and $\phi = 1.67$ (RFL).

   Making suitable assumptions to simply the flow set up, *estimate* the point of maximum temperature in the region between the two flames in the z-space and the value of the maximum temperature. It is given that the the adiabatic flame temperatures of the lean and rich flame are 1650 K and 1914 K respectively. Further, the equilibrium composition (in terms of mass fractions) post the lean flame is $Y_{O_2} = 0.09$ (rest are inert) and post the rich flame is $Y_{CO} = 0.07, Y_{H_2} = 0.004$ (rest are inert).

2. (2 points) A classical bunsen burner used in glass blowing units is shown. Note that the air vent is open. Typical fuels used in such burners are kerosene, LPG, and acetylene. Consider the following cases:

   (a) The bunsen burner is designed to operate with LPG/air mixtures and the certain critical flow velocity gradient *above* which the flame is stable is identified. While operating close and yet above this critical point, a researcher is letting in acetylene/air by mistake into such a burner. What do you expect to see? Justify your answer.

   (b) The bunsen burner is designed to operate with acetylene/air mixtures and the certain critical flow velocity gradient *below* which the flame is stable is identified. While operating close and yet below this critical point, a researcher is letting in LPG/air by mistake into such a burner. What do you expect to see? Justify your answer.



3. (5 points) Design a natural-gas burner for a commercial cooking range that has a number of circular ports arranged in a circle. The circular diameter of the burner head is constrained to 160 mm. At full load, the burner must deliver 2.2 kW and operate with 40% primary aeration. For stable operation, the loading of an individual port should not exceed 10W per mm^2 of port area. Also, the full-load flame height should not exceed 20 mm. Determine the number of ports, diameter of the ports, and the spacing between them.

   The port diameter should be less than 3 mm to ensure quenching in the event of flashback. The flame height is given as, $L_f = 1300\dot{V}_p(T_\infty/T_F)/\ln(1 + 1/S)$, where L_f is flame height in mm, $\dot{V}_p$ is the volume flow rate in m^3/s per port, S is the molar ratio of the ambient fluid to the partially premixed aerated fuel-air mixture entering the ports to ensure stoichiometric conditions are met at the burner exit. Take heating value of natural gas as 50 MJ/kg and $T_\infty = T_F = 300\,\mathrm{K}$, and assume that natural gas is all methane in composition.

4. (4 points) Explain the following with respect to domestic cooking stove burner:

   (a) Increase in port loading (W per unit area) increases the tendency to lift off

   (b) Increase in port diameter reduces the tendency to lift

   (c) Smaller port diameter reduces tendency to flash back.

   (d) When the burner is heated up, the flame is more resistant to lift off.

5. (3 points) Explain briefly the Lean Premixed Combustion concept for stationary gas turbines, highlighting the advantages and challenges in its implementation.

6. (4 points) An atmospheric pre-vaporizer burner has a power rating of 5 kW. It operates with kerosene (boiling point 225°C, latent heat of vaporization 250 kJ/kg and specific heat 2 kJ/kg-K), which is fed at a temperature of 25°C. Its calorific value is 43 MJ/kg and the average heat flux from the flame to the tube carrying the liquid fuel is 60 kW/m^2 . If the tube is made of copper and has a diameter of 10 mm, determine the length of the tube to pre-vaporize kerosene.

7. (1 + 1 + 2 points) Answer the following in the context of droplet burning:
   (a) In deriving the equations, the gas phase is assumed to be in *'quasi-steady state'*. Explain the basis for this approximation.
   (b) What do you understand by the term *'blocking effect'*?
   (c) Comment on how different the transfer number is between a case where the ambient oxidizer is air vs pure oxygen. What effect do these different oxidizers have on the mass burning rate of the droplet (little or a lot)? Justify your answer based on the underlying physics.

8. (3 + 3 + 7 + 2 points)
   (a) Evaluate B (transfer number) for n-octane (C_8H_{18}) burning in air at 500 °C and 2×10^6 N/m^2, given the following data: heat of combustion of n-octane = 44.3 MJ/kg; T_{BP} = 281 °C; latent heat of vaporization = 120 kJ/kg; specific heat = 2.09 kJ/kg.
   (b) Evaluate the burning time of a droplet of n-octane burning as above, given that its initial diameter is 200 μm, and that ρ_{liq} = 706 kg/m^3 and λ = 0.0729 W/m-K.
   (c) For a case of a small droplet (say $< 25\mu m$), the droplets vaporize quickly without any flame surrounding the droplet. For this scenario, obtain the rate of vaporization of the droplet (mass loss rate), given that the hot ambient is at temperature T_f.
   (d) If the expression for transfer number obtained in (c) above were to be used to determine the transfer number of a burning droplet whose flame temperature is T_f, is that a good approximation? Justify your answer.

9. (2 points) The droplet number distribution from a twin-fluid atomizer takes this form,

$$\frac{dN}{dD} = D\exp(-D),$$

where D denotes the droplet diameter and dN denotes the number of droplets having a diameter between D and $D + dD$. Sketch the number distribution as a function of droplet diameter D, and find the sauter-mean diameter. You may use any mathematical tools to obtain the integrals involved.

10. (4 points) Consider the burning rate of a single C particle based on the one-film model. Obtain the conditions under which the burning is kinetically controlled vs diffusion controlled.

11. (4 points) Using the elemental analysis given in the table below for typical biomass and coal calculate the stoichiometric air to fuel ratio.

Element	Biomass	Coal
C%	51.32	89
H%	5.62	6.1
N%	0.23	2.6
O%	rest	rest

12. (4 points) A fluidized bed combustor operates at 5 bar pressure and 900°C bed temperature. Coal particles with a mean (sphere) diameter of 6 mm and average density of 1250 kg/m^3 are used. Calculate the minimum air velocity from the distributor plate that will fluidize the coal particles. The coefficient of drag may be assumed as 0.45.

13. (4 points) If producer gas (Hydrogen 15%, Carbon Monoxide 22%, and rest N_2 by volume) obtained from biomass gasification is to be used in an atmospheric entrained burner designed for LPG with the same power rating, list the changes to be made (if any) in the orifice, diffuser throat and burner head, relative to the existing values.