Question 1

(a) Determine the products for the reaction:

\[ C_{11}H_{23} + 16 (O_2 + 3.76 N_2) \rightarrow b \text{ CO}_2 + c \text{ CO} + d \text{ H}_2 \text{O} + e \text{ H}_2 + f \text{ N}_2 \]

at 2400 K, 15 atm pressure in a gas turbine combustor, using the water-gas shift reaction:

\[ \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 \]

[15 marks]

For the reaction

\[ C_{x}H_{y} + a (O_2 + 3.76 N_2) \rightarrow b \text{ CO}_2 + c \text{ CO} + d \text{ H}_2 \text{O} + e \text{ H}_2 + 3.76a \text{ N}_2. \]

\[ K_p = \exp(-\Delta G/R_u T) = \frac{b \cdot e}{c \cdot d}, \quad R_u = 8.3143 \text{ J/mole.K} \]

\[ b = \frac{2a(K_p - 1) + x + y/2}{2(K_p - 1)} \quad \sqrt{[2a(K_p - 1) + x + y/2]^2 - 4K_p(K_p - 1)(2ax - x^2)} \]

\[ g_f^{0}(\text{CO}_2,2400K) = -396.230 \text{ kJ/mole}, \quad g_f^{0}(H_2,2400K) = 0 \text{ kJ/mole}, \]

\[ g_f^{0}(\text{CO},2400K) = -319.057 \text{ kJ/mole}, \quad g_f^{0}(H_2O,2400K) = -112.386 \text{ kJ/mole} \]

(b) Consider the equilibrium reaction \( H_2 \leftrightarrow H + H \) in a steady flow reaction chamber (a rocket burner). The burner reacts oxygen and hydrogen according to the reaction:

\[ 2.4 \text{ H}_2 + \text{ O}_2 \rightarrow 1.910 \text{ H}_2\text{O} + a \text{ H}_2 + b \text{ H} + 0.040 \text{ OH} + 0.022 \text{ O}_2 + 0.004 \text{ O} \]

Determine the mole fractions of H\(_2\) and H in the vessel for \( T = 3000 \text{ K} \), \( p = 1 \text{ atm} \).

[10 marks]

\[ g_f^{0}(H_2,3000K) = 0 \text{ kJ/mole}, \quad g_f^{0}(H,3000K) = 46.182 \text{ kJ/mole} \]
Question 2

Consider the following chain-reaction mechanism for the low pressure formation of water:

\[
\begin{align*}
H_2 + O_2 & \xrightarrow{k_1} OH + OH \\
OH + H_2 & \xrightarrow{k_2} H_2O + H \\
H + O_2 & \xrightarrow{k_3} OH + O \\
O + H_2 & \xrightarrow{k_4} OH + H \\
H + OH + M & \xrightarrow{k_5} H_2O + M
\end{align*}
\]

(a) Write out expressions for \( \frac{d[OH]}{dt} \), \( \frac{d[O]}{dt} \) and \( \frac{d[H]}{dt} \). [6 marks]

(b) Assuming the concentrations of OH, O and H radicals are in equilibrium, show that:

(i) \( [O]_{eq} = \frac{k_1[H]_{eq}[O_2]}{k_4[H_2]} = \frac{k_2k_3[O_2]}{k_4k_5[M]} \) [5 marks]

(ii) \( [H]_{eq} = \frac{k_2[H_2]}{k_5[M]} \) [5 marks]

(iii) \( [OH]_{eq} = \frac{k_1[O_2]}{k_2} + \frac{k_3[O_2]}{k_5[M]} \) [9 marks]
Question 3

(a) Explain the chemistry underlying the first and second explosion limits in the hydrogen-oxygen system shown in Figure Q3 below. [8 marks]

(b) Given the hydrogen-oxygen combustion mechanism in the data sheet, and the branching factor $\phi = 2k_1 - k_8[M]$, determine the second limit critical pressure for explosion at 500 °C. [7 marks]

(c) A spark ignition engine adapted to burn butane has a compression ratio of 11. After compression and initial combustion, the unburned mixture attains a temperature and pressure of 750 K and 20 atm respectively. Determine the time the stoichiometric mixture will take to auto-ignite, given the global rate of reaction in the form:

$$\dot{C}_{H_{10}} = \frac{d[C_4H_{10}]}{dt} = -7.4 \times 10^{11} \left( \text{cm}^3 / \text{mole} \right)^{0.7} \text{s}^{-1} \left( \frac{125.528 \text{kJ}}{R^c T} \right) \left[ C_4H_{10} \right]^{0.1} \left[ \text{O}_2 \right]^{1.60}$$

and the ignition delay in the form:

$$t_{\text{ign}} = \beta = \left( \frac{R_u T_0^2}{E_a} \right) \frac{\rho c_v}{C_{H_{10}} \Delta u_r},$$

given $c_v = 900 \text{ J/kg.K}$, $R = 287 \text{ J/kg.K}$, $R_u = 8.3142 \text{ J/mole.K}$, $\Delta u_r = -2662.4$ kJ/mole. [10 marks]
Question 4

(a) Using the results obtained from the simplified laminar flame analysis, estimate the local velocity of a laminar flamelet in a methane fuelled premixed combustor for the following conditions: $\phi = 1.0$, $T_u = 750$ K, $p = 15$ bar.

[10 marks]

Note: $S_L(\text{methane-air}, \phi = 1.0, T_u = 300$ K, $p = 1$ bar) = 40 cm/s.

$T_b(\text{methane-air}, \phi = 1.0, T_u = 300$ K, constant pressure) = 2250 K.

$S_L \propto T_u^{-0.375} T_b^{-n/2} \exp\left(-20131K/T_b\right)$, $n(\text{methane-air}) = 1.00$

(b) Determine the laminar flame speed of a propagating stoichiometric methane-air flame subject to the conditions described in (a) above, using Metghalchi and Keck’s empirical formula, given below. [7 marks]

$$S_L = S_{L,ref} \left( \frac{T_u}{T_{u,ref}} \right)^\gamma \left( \frac{p}{p_{ref}} \right)^\beta, \quad \gamma = 2.18 - 0.8(\phi - 1), \quad \beta = -0.5 + 0.22(\phi - 1),$$

$$S_{L,ref}(\text{CH}_4, 298K, 1\text{bar}) = 40.0 \text{ cm/s} - 124.6 \text{ cm/s} (\phi - 1.08)^2,$$

(c) Given that the minimum ignition energy for a stoichiometric mixture of kerosene with air at ambient conditions ($p = 100$ kPa, $T = 298$ K) is 40 mJ, estimate the minimum ignition energy required to ignite a stoichiometric mixture of kerosene and air in a gas turbine engine combustor during flight at 13000m altitude ($p = 22$ kPa, $T = 215$ K), and comment on the implications of your result for gas turbine ignition systems. [8 marks]

$$E_{ign} \propto \frac{T^{1.125}}{p^2} \exp\left(-15098K/T_b\right),$$

$T_b(\text{kerosene-air}, \phi = 1.0, T_u = 300$ K, $p = 1$ bar) = 2300 K.
Question 5

(a) You are asked to design a 100 kW boiler burner using 1000 laminar ethane-air jet flames arranged in a 40 x 25 matrix burner. Using the laminar, isothermal jet model with a jet Reynolds number of 50, determine the flame height, the nozzle diameter and jet exit velocity for the jet emanating from the burner nozzles, assuming the ambient conditions are at 300 K and 100 kPa.

\[ y_f(x,0) = \frac{3J_e}{8\pi \rho \nu_e D} = \frac{3V_e}{8\pi D_x}, \quad R = 287 \text{ J/kg.K}, \quad D = 1.590 \times 10^{-5} \text{ m}^2/\text{s}, \]

LCV (ethane) = 47.489MJ/kg. [10 marks]

(b) Using Roper’s experimental correlation specified below, determine the actual jet flame height for the jets emanating from the burner nozzles. [5 marks]

\[ L_{f,\text{exp}} = \frac{1330\hat{V}_f T_w}{T_f \ln(1+1/S)} \]

(c) (i) By analogy with the definition of the laminar burning velocity, define the turbulent burning velocity \( v_t \) for a turbulent flame propagating through a turbulent, premixed fuel-air mixture. [3 marks]

(ii) Hence, using usual notation, show that \( v_t = \frac{S_f A_{\text{vap}}}{A} \). [2 marks]

(d) Turbulent combustion in a premixed pre-vapourised combustor continuously consumes 1.2 kg/min kerosene and 18 kg/min of air operating with an unburned temperature and pressure of 700 K and 1.2 MPa respectively. The mean flame area was measured to be approximately 100 cm\(^2\). Determine the turbulent flame speed of the kerosene-air mixture. [5 marks]
Question 6

(a) A large electricity generator produces 1GWe power. Such generation scale will either be nuclear fuel or fossil fuel base. If the fuels used are natural gas, oil or coal:

(i) explain the different abatement techniques that the plant will need to make use of to minimise the emissions of air pollutants, [7 marks]
and
(ii) draw a flow diagram to explain ‘carbon capture’. [5 marks]

(b) (i) Describe the concept of knock and its characteristics in spark-ignition gasoline engines, [5 marks]
(ii) When is more likely for knock to occur? Under what engine and environmental conditions? [4 marks]
(iii) Describe various means for reducing the chances of knock in the cylinder of gasoline engines. [4 marks]
### 1. H2-O2 MECHANISM

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<th>Reaction</th>
<th>A (mol, cm³, s⁻¹)</th>
<th>b (kJ/mol)</th>
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<tr>
<td>O₂ + H = OH + O</td>
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<tr>
<td>H₂ + O = OH + H</td>
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<td>OH + OH = H₂O + H</td>
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### 2. RECOMBINATION REACTIONS

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<th>b (kJ/mol)</th>
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<td>H + H + M' = H₂ + M'</td>
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<td>H + OH + M' = H₂O + M'</td>
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<td>O + O + M' = O₂ + M'</td>
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### 3. HO₂ FORMATION/CONSUMPTION

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<th>Reaction</th>
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<td>H + O₂ + M' = HO₂ + M'</td>
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<td>HO₂ + O + O₂ = H₂O + O₂</td>
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### 4. H₂O₂ FORMATION/CONSUMPTION

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<th>A (mol, cm³, s⁻¹)</th>
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<td>HO₂ + HO₂ = H₂O₂ + O₂</td>
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<td>OH + O₂ + M' = H₂O₂ + M'</td>
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