***Note: To answer the following questions, feel free to incorporate your own assumptions whenever necessary. And it is a kind reminder that not every term appearing in a question will be present in its answer.

1. A plant factory utilizes synthetic sunlight (LED), supplied carbon dioxide (CO_2), and nutrient solution (H_2O with nutrient ions) to grow pathogen-free, ready-to-eat vegetables in a clean room. For simplicity, the vegetable growth can be described by the well-known photosynthesis reaction,

$$6\,CO_2 + 12\,H_2O \xrightarrow{hv\ \&\ nutreint\ ions} C_6H_{12}O_6\ (plant\ structure) + 6\,H_2O$$

A researcher finds that a vegetable's weight W (in grams) doubles in every T days in a specific growth period at 20 °C, and T is independent of any concentration.

(a) What is the reaction order of the vegetable growth kinetics? Why? (4%)

(b) Assume that the supplied CO_2 concentration is P_0 ppm. Determine the rate constant k for the specific growth period. Include the unit in your answer. (5%)

(c) In a further study, the researcher discovers that the rate constant k is correlated to the irradiant LED (hv) intensity I (W/m^2) and nutrient ion concentration C (mM) by the following equation: $k = k_0 I^a C^b$

Describe how to determine k_0, a, and b, respectively, from experiments. (5%)

2. An antigen (A, e.g., an avian H5N2 virus) specifically and reversibly binds to its antibody (B, e.g., anti-H5N2 IgG) to form an immuno-complex (AB) via a simple one-site binding mechanism, which comprises a forward association reaction and a reversed dissociation reaction as shown below.

$$A + B \overset{k_1}{\rightarrow} AB$$

$$AB \overset{k_2}{\rightarrow} A + B$$

A researcher uses a SPR (surface plasmon resonance) sensor chip immobilized with a fixed molar concentration of antibody B, C_{B0}, to simultaneously monitor the binding of a flow-through antigen A. The SPR assay is performed by two steps: (i) *Step I: from t (time) = 0 (start of antigen binding) to t =* T_1 *(approaching saturated binding)* – continuously deliver a buffer solution containing antigen A with a constant molar concentration, C_{A0}, to interact with the immobilized antibody B and to form the complex AB on the SPR chip surface. (ii) *Step II: from t =* T_1 *(start of antigen elution) to t =* T_2 *(approaching complete dissociation)* – continuously deliver an elution solution containing neither antigen A nor antibody B to dissociate complex AB. During the assay, the transient (time-dependent) SPR sensor signal S is recorded and is proportional to the molar concentration of complex AB on the sensor chip, C_{AB}. That is, $S(t) = \alpha\, C_{AB}(t)$.

(a) Solve $S(t)$ for *Step I* (for $0 \le t < T_1$). (7%)

(b) Solve $S(t)$ for *Step II* (for $T_1 \le t < T_2$). (5%)

(c) Draw a plot of S against t (known as a sensorgram) for the two-step real-time SPR assay of the antigen-antibody binding. (5%)

(d) Describe how to determine the dissociation constant (K_d) of this binding event from the plot of (c). (5%)

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3. An inactive pro-drug (A) needs the liver in a human body to activate it to become a therapeutically functional drug (A*). The activation process can be described as the following first-order reaction.

$$A \xrightarrow{\text{liver cells}} A^*$$

For *in vitro* pharmacokinetic study, a researcher employs an "organ-on-a-chip" technology and fabricates a microfluidic chip with a micro-tubular bioreactor (having a length of L and a radius of R) that fills with cultured liver cells (having a weight of W and a density of ρ) as biocatalysts for pro-drug activation. In the study, the inlet molar flow rate, volumetric flow rate, and molar concentration of the pro-drug A are F_{A0}, v_0, and C_{A0}, respectively, and the micro-bioreactor is operated at 37°C.

(a) Give an appropriate SI unit for the rate constant of the activation reaction. (4%)

(b) Determine the cell volume (V) required to fill in the micro-bioreactor to attain a conversion of X for the pro-drug activation. (5%)

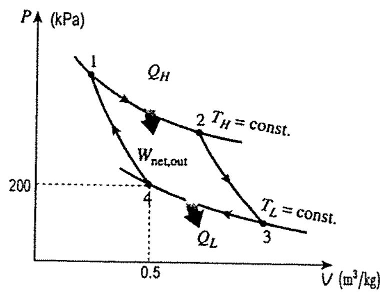
(c) Describe the minimal micro-bioreactor length L and the corresponding space time τ for attaining the conversion X. (5%)

4. Starting from the definition of enthalpy, $H = U + Pv$ and additional relations based on the First and Second Laws of Thermodynamics, derive the following:

(a) Equations for $(\partial H/\partial P)_S$ and $(\partial H/\partial S)_P$. (4%)

(b) The maximum amount of nonexpansion work done by a system. (6%)

5. The net work output of a Carnot engine is 200 kJ. Determine the required heat addition and T_H if the cycle efficiency is 60%. The working fluid is air. Please state all your assumptions. (P in kPa, v in m^3/kg) (10%)



6. Draw the entropy vs. temperature diagram for water from solid to liquid and then to gas phase, schematically. (5%)

7. For the following processes, state whether each of the thermodynamics quantities ΔG, ΔH, and ΔS of the system increase, decrease or do not change. Explain your answers briefly.

(a) A system contains a 1 M sucrose solution and pure water separated by a membrane permeable to water only. A small amount of water is transferred through the membrane from the pure water to the sucrose solution at constant temperature and pressure. (6%)

(b) Liquid water at 99.64 °C, 1 bar pressure is evaporated to water vapor at 99.64°C, 1 bar pressure. The system is water. (6%)

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8. Carbon dioxide hydrate is one form of hydrate structure. The dissociation of CO_2 hydrate can take on two ways, *i.e*, to gaseous CO_2 and liquid water and to gaseous CO_2 and ice, respectively.

$$CO_2 \cdot nH_2O_{(s)} \rightleftarrows CO_{2(g)} + nH_2O_{(l)} \quad \text{(I)}$$

$$CO_2 \cdot nH_2O_{(s)} \rightleftarrows CO_{2(g)} + nH_2O_{(s)} \quad \text{(II)}$$

The melting of ice to liquid water is known as

$$nH_2O_{(s)} \rightleftarrows nH_2O_{(l)} \quad \text{(III)}$$

where the enthalpy change of fusion per mole of water is 6.01 kJ/mol. The temperature vs. pressure change for reaction (II) is as follows.

T (K)	P (MPa)
272.15	1.120
273.15	1.225
274.15	1.377

(a) Estimate the molar enthalpy change for reaction (II) at 0°C. (7%)

(b) If the hydration number n is six, estimate the molar enthalpy change for reaction (I). Please state all your assumptions clearly. (6%)

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