1. (20p) A complete-mix flow reactor is designed to treat an influent waste stream containing 130 mg/L of casein at a flow rate of 380 liters per minute (Lpm). Assume that casein removal follows first-order removal kinetics with a rate constant $k$ of 0.5 h$^{-1}$ and that the effluent should contain 13 mg/L of casein at steady state. Determine:
   a. The detention time in hours.
   b. The volume of the reactor in cubic meters.

2. (30p) A 1000 MW coal-fired power plant has a 33% efficiency of converting the energy of coal into electrical energy. The coal has an energy content of 25 kJ/g and contains 60% C, 3% S, and 9% ash. Also assume that 70% of the ash in the coal is released as fly ash with 30% of it settling outside of the firing chamber where it is collected as bottom ash. Approximately 20% of the waste heat is assumed to exit in the stack gases, and the cooling water dissipates the remaining heat. Assume that air emission standards restrict S and particulate quantities to 250 g SO$_2$ per $10^6$ kJ of heat input and 10 g particulates per $10^6$ kJ of heat input into the coal-fired power plant. Perform a materials and energy balance around the coal-fired power plant to answer the following questions and draw a simplified schematic of the process. Determine:
   a) The quantity of heat loss to the cooling water (MW).
   b) The quantity of the cooling water (kg/s) and flow rate (m$^3$/s), assuming a 15°C increase in the temperature of the cooling water.
   c) The efficiency of the SO$_2$ removal system to meet air emission standards.
   d) The efficiency of the particulate removal system to meet air emission standards.

3. (20p) A step-aeration activated sludge process treats 38,000 m$^3$/d of wastewater containing 220 g/m$^3$ BOD$_5$. The F/M ratio based on VSS in the aeration basin is 0.30 d$^{-1}$ and the MLVSS concentration is 3000 g/m$^3$. Determine the following:
   a) The aeration basin volume (m$^3$).
   b) The detention time (h).
   c) The effluent substrate concentration if the specific substrate utilization rate is 0.28 d$^{-1}$.
   d) Substrate removal efficiency (%).

4. (30p) Determine the size of the landfill having a geometry of a truncated pyramid with a square base required to serve a city with a population of 100,000 growing at a rate of 5% per year for 10 years. The city has a constant waste generation rate of 2 kg/capita/day and recycling rate of 35%. Assume that the waste occupies 90% of the landfill volume with the in-place waste density of 900 kg/m$^3$, landfill height of 30 m and side slopes of 3.5:1 (run:rise).
1. a) Substitute the influent and effluent casein concentration and the rate constant $k$ into the corresponding CMFR (Complete-Mix-Flow Reactor) equation (Eqn.5.73/p.212) given in the textbook (Textbook: Mines O. Richard; Environmental Engineering: Principles and Practice, Wiley Blackwell, 2014, ISBN: 978-1-118-80145-1) to calculate the detention time as follows:

$$
\tau = \frac{V}{Q} = \frac{C_0 - C_e}{kC_t} = \frac{(130 \text{mg/L} - 13 \text{mg/L})}{(0.5 \text{h}^{-1})(13 \text{mg/L})} = 18 \text{ h}
$$

a) The volume of the complete-mix reactor is calculated by multiplying the detention time by the flow rate as follows:

$$
V = (\tau)(Q) = (18 \text{ h}) \left( 380 \frac{L}{min} \right) \left( \frac{60 \text{ min}}{h} \right) \left( \frac{m^3}{1000 \text{ L}} \right) = 410.4 \text{ m}^3
$$

2. a) Perform the energy balance around the coal-fired power plant as follows:

$$
\text{[the rate at which the energy enters CV]} - \text{[the rate at which the energy leaves CV]}
$$

Recall that at steady-state, the energy accumulated is zero and the equation reduces to the following form:

$$
\text{[the rate at which the energy enters CV]} = \text{[the rate at which the energy leaves CV]}
$$

B) We estimate the energy in the coal by dividing the useful energy produced as electrical power by the efficiency of the coal-fired power plant as follows:

$$
\text{input power} = \frac{\text{output power}}{\text{efficiency}} = \frac{1000 \text{ MW}_e}{0.33} = 3030 \text{ MW}_t
$$

Determine the total energy losses in the system as follows:

$$
\text{total losses} = \text{energy input} - \text{energy output} = 3030 - 1000 = 2030 \text{ MW}_t
$$

Estimate the stack losses assuming 20% of the total energy losses as follows:

$$
\text{stack losses} = (0.20)(2030 \text{ MW}_t) = 406 \text{ MW}_t
$$

Calculate the energy loss in the cooling water:

$$
\text{[energy in coal]} = \text{energy out in stack gases} + \text{energy out in cooling water} + \text{energy out useful electrical power}
$$

$$
[3030 \text{ MW}_t] = [406 \text{ MW}_t] + \text{[energy out in cooling water]} + [1000 \text{ MW}_e]
$$

b) The mass flow rate ($\dot{m}$) of water required for cooling is calculated as follows:

$$
\dot{m} = 1624 \text{ MW}_t \times \left( 4.18 \frac{kJ}{kg \cdot ^\circ C} \right) \left( 15^\circ C \right) \left( \frac{1000 \text{ J}}{kJ} \right) \left( \frac{1 \text{ MW}}{10^6 \text{ J}} \right) \rightarrow \dot{m} = 2.59 \times 10^4 \frac{kg}{s}
$$

The volumetric flow rate of the cooling water is determined by dividing the mass flow rate by the density of the water (1000 kg/m$^3$) as follows:
\[ Q = \frac{\dot{m}}{\rho} = \frac{2.59 \times 10^4 \text{kg}}{1000 \text{kg/m}^3} = 25.9 \text{ m}^3/\text{s} \]

c) Calculate the quantity of SO\(_2\) produced and that can be emitted per unit of heat input into the coal-fired power plant. First calculate the quantity of heat input into the coal-fired power plant as follows:

\[ \text{Heat input} = 3030 \text{ MW} \left( \frac{10^6 \text{W}}{1 \text{MW}} \right) \left( \frac{1 \text{ kW}}{1000 \text{ W}} \right) \left( \frac{24 \text{ h}}{1 \text{ d}} \right) \left( \frac{1 \text{ kJ}}{\text{s}} \right) \left( \frac{3600 \text{ s}}{1 \text{ h}} \right) = 2.62 \times 10^{11} \text{ kJ/d} \]

The quantity of coal input into the coal-fired power plant:

\[ \text{quantity of coal burned daily} = \frac{2.62 \times 10^{11} \text{ kJ/d}}{25 \text{ kJ/1 kg coal}} \left( \frac{1 \text{ kg}}{1000 \text{ g}} \right) = 1.048 \times 10^7 \text{ kg coal/d} \]

Next determine the quantity of SO\(_2\) that is produced daily knowing that the molecular weight of sulfur dioxide is 32+2(16)=64

\[ \text{SO}_2 \text{ produced} = \frac{1.048 \times 10^7 \text{ kg coal/d}}{0.03 \text{ kg S/kg coal}} \left( \frac{64 \text{ kg SO}_2}{32 \text{ kg S}} \right) = 6.288 \times 10^5 \text{ kg SO}_2/\text{d} \]

The quantity of SO\(_2\) that is permitted to be discharged daily to the atmosphere is calculated as follows:

\[ \text{SO}_2 \text{ discharged} = \left( 250 \text{ g SO}_2 \left( \frac{10^6 \text{ kJ}}{1 \text{ g SO}_2} \right) \right) \left( \frac{2.62 \times 10^{11} \text{ kJ/d}}{1 \text{ kg}} \right) \left( \frac{1 \text{ kg}}{1000 \text{ g}} \right) = 6.55 \times 10^4 \text{ kg SO}_2/\text{d} \]

The efficiency of air pollution control equipment can be calculated from the following definition:

\[ \text{removal efficiency (\%)} = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \times 100 = \frac{M_{\text{in}} - M_{\text{out}}}{M_{\text{in}}} \times 100 \]

\[ \text{SO}_2 \text{ removal efficiency (\%)} = \frac{(6.288 \times 10^5 \text{ kg SO}_2/\text{d}) - (0.655 \times 10^5 \text{ kg SO}_2/\text{d})}{(6.288 \times 10^5 \text{ kg SO}_2/\text{d})} \times 100 = 89.6\% \]

b) Determine the quantity of particulates or fly ash that enters the air pollution control equipment as follows:

\[ \text{fly ash produced} = \frac{1.048 \times 10^7 \text{ kg coal/d}}{0.09 \text{ kg ash/kg coal}} \left( \frac{0.70 \text{ kg fly ash}}{\text{kg ash}} \right) = 6.60 \times 10^5 \text{ kg fly ash/d} \]

The quantity of fly ash or particulate matter that is permitted to be discharged daily to the atmosphere is calculated as follows:

\[ \text{fly ash discharged} = \left( 10 \text{ g particulates} \left( \frac{10^6 \text{ kJ}}{1 \text{ g particulates}} \right) \right) \left( \frac{2.62 \times 10^{11} \text{ kJ/d}}{1 \text{ kg}} \right) \left( \frac{1 \text{ kg}}{1000 \text{ g}} \right) = 2.62 \times 10^3 \text{ kg particulates/d} \]

Estimate the particulate removal efficiency to meet air standards:

\[ \text{particulate removal efficiency (\%)} = \frac{(6.60 \times 10^5 \text{ kg fly ash/d}) - (2.62 \times 10^3 \text{ kg fly ash/d})}{(6.60 \times 10^5 \text{ kg fly ash/d})} \times 100 = 99.6\% \]

A simplified schematic of the materials and energy flow through the coal-fired power plant can be presented like in the textbook given on p.230 (Figure E5.11).
3. a) Calculate the volume using the definition of $F/M$ ratio as follows: The detention time is given as 6 h to substitute in the definition of it as follows:

$$F/M = \frac{Q S_i}{XV} = \frac{(38000 \frac{m^3}{d}) (220 \frac{g}{m^3})}{(3000 \frac{g}{m^3}) (9289 m^3)} = 0.30 \frac{g \text{BOD}_5}{g \text{VSS} \cdot d} \rightarrow V = 9289 \text{ m}^3$$

b) 

$$\tau = \frac{V}{Q} = \frac{9289 m^3}{38000 \frac{m^3}{d}} \left( \frac{24 \text{ h}}{d} \right) = 5.9 \text{ h}$$

c) The effluent substrate concentration in terms of BOD$_5$ is determined by rearranging the definition equation of $U$ as follows:

$$U = \frac{Q(S_i - S_e)}{XV} = \frac{(38000 \frac{m^3}{d}) (220 \frac{g}{m^3} - S_e \frac{g}{m^3})}{(3000 \frac{g}{m^3}) (9289 m^3)} = 0.28 \frac{g \text{BOD}_5}{g \text{MLVSS} \cdot d} \rightarrow S_e = 14.7 \frac{g}{m^3}$$

d) Treatment efficiency is calculated using the following equation:

$$E(\%) = \frac{C_i - C_e}{C_i} \times 100$$

$$E(\%) = \frac{220 \frac{g}{m^3} - 14.7 \frac{g}{m^3}}{220 \frac{g}{m^3}} \times 100 = 93.3\%$$

4. Waste Volume Calculation Table

<table>
<thead>
<tr>
<th>Year</th>
<th>Population</th>
<th>Waste Generation Rate (kg/person/day)</th>
<th>Waste disposed (kg)</th>
</tr>
</thead>
<tbody>
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<td>4.75x10$^7$</td>
</tr>
<tr>
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<td>105000</td>
<td>2</td>
<td>4.98x10$^7$</td>
</tr>
<tr>
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<td>2</td>
<td>5.23x10$^7$</td>
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<td>2</td>
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<td>6.36x10$^7$</td>
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<tr>
<td>10</td>
<td>155133</td>
<td>2</td>
<td>7.36x10$^7$</td>
</tr>
</tbody>
</table>

Total waste disposed: 5.97x10$^8$ kg

In-place waste density: 900 kg/m$^3$ waste → Total volume of waste disposed: 6.63x10$^5$ m$^3$

Waste as % of Landfill volume: 90% → Landfill volume required = 7.37x10$^5$ m$^3$
The landfill height given $H = 30 \text{ m}$, side slopes with $N = 3.5$ (3.5 run:1 rise) → solve Eq.8.12 given in the textbook on p.461-462 as follows:

\[
V_L = (L^2 - 2HNL + 2H^2N^2)H
\]

\[
7.37\times10^5 \text{m}^3 = [L^2 - 2(30 \text{ m})(3.5)L + 2(30 \text{ m})^2(3.5)^2](30 \text{ m})
\]

\[
L^2 - 210L - 2516.7 = 0
\]

\[
L_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{-(-210) \pm \sqrt{(-210)^2 - 4(1)(-2516.7)}}{2(1)} = \frac{210 \pm 232.7}{2}
\]

→ $L = 222 \text{ m}$ (length and width of base)