

**Basic Environmental Engineering and Pollution Abatement**  
**Professor Prasenjit Mondal**  
**Department of Chemical Engineering**  
**Indian Institute of Technology, Roorkee**  
**Lecture 10**  
**Tutorial -2**

Hello everyone. Now, we will have a tutorial session and now we will solve some numerical problems based on our discussion during last four classes.

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Problem 1

A confined aquifer 25 m thick has two monitoring wells spaced 600 m apart along the direction of groundwater flow. The difference in water level in the wells is 3 m (the difference in piezometric head). The hydraulic conductivity is 50 m/day. Estimate the rate of flow per meter of distance perpendicular to the flow.

**Solution:**

The gradient is

$$dh/dL = 3.0\text{m}/600\text{m} = 0.005$$

Using Darcy's law, with an arbitrary aquifer width of 1 m, yields

$$Q = KA(dh/dL) = 50 \text{ m/d} * 1.0 \text{ m} * 25 \text{ m} * 0.005 = 6.25 \text{ m}^3/\text{day per meter of width.}$$

$Q = KA \frac{dh}{L}$

Our first problem statement is a confined aquifer 25 m thick has two monitoring wells spaced 600 m apart along the direction of groundwater flow. The difference in water level in the wells is 3 m. The difference in piezometric head. The hydraulic conductivity is 50 m/d. Estimate the rate of flow per meter of distance perpendicular to the flow.

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## Problem 2

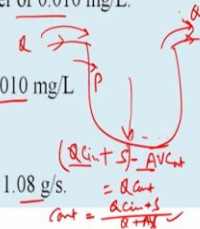
A phosphorus limited lake with surface area equal to  $90 \times 10^6 \text{ m}^2$  is fed by a  $18 \text{ m}^3/\text{s}$  stream that has a phosphorus concentration of  $0.010 \text{ mg/L}$ . In addition, effluent from a point source adds  $0.9 \text{ g/s}$  of phosphorus. The phosphorus settling rate is estimated as  $10 \text{ m/yr}$ .

- Estimate the average total phosphorus concentration.
- What rate of phosphorus removal at the wastewater treatment plant would be required to keep the concentration of phosphorus in the lake at an acceptable level of  $0.010 \text{ mg/L}$ .

**Soln.**

Phosphorus loading from the incoming stream  $QC_{in} = 18.0 \text{ m}^3/\text{s} \times 0.010 \text{ mg/L}$   
 $= 18.0 \text{ m}^3/\text{s} \times 0.010 \text{ g/m}^3 = 0.18 \text{ g/s}$

Adding  $0.9 \text{ g/s}$  from the point source a total phosphorus input rate of  $1.08 \text{ g/s}$ .



Now, problem number 2. A phosphorous limited lake with surface area equal to  $90 \times 10^6 \text{ m}^2$  is fed by  $18 \text{ m}^3/\text{s}$  stream that has a phosphorous concentration of  $0.010 \text{ mg/L}$ . In addition, effluent from a point source adds  $0.9 \text{ g/s}$  of phosphorous. The phosphorous settling rate is estimated as  $10 \text{ m/y}$ .

Estimate the average total phosphorous concentration. Question number 1 a). And b) part. What rate of phosphorus removal at the wastewater treatment plant would be required to keep the concentration of phosphorus in the lake at an acceptable level of  $0.010 \text{ mg/L}$ . So, the problem is like this.

Phosphorus loading from the incoming stream  $QC_{in} = 18.0 \text{ m}^3/\text{s} \times 0.010 \text{ mg/L} = 0.18 \text{ g/s}$ .

Adding  $0.9 \text{ g/s}$  from the point source a total phosphorus input rate  $= 0.18 + 0.9 = 1.08 \text{ g/s}$

The phosphorous settling, the phosphorus is settled here and settling rate is  $10 \text{ m/yr}$ . So, that we have to calculate, what is the settling rate?

$V_s = 10 \text{ m/year}$

$= 10 / (365 \times 24 \times 3600) \text{ m/s} = 3.17 \times 10^{-7} \text{ m/s}$

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The estimated settling rate is :

$$V_s = 10 \text{ m/year}$$

$$= 10 / (365 \times 24 \times 3600) \text{ m/s} = 3.17 \times 10^{-7} \text{ m/s}$$

Steady state concentration of total phosphorus would be:

$$C_c = (QC_{in} + S) / (Q + V_s A) = 1.08 / (18 + 3.17 \times 10^{-7} \times 90 \times 10^6) \text{ g/m}^3 = 0.023 \text{ mg/L}$$

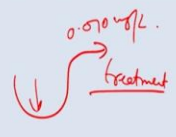
Which is above 0.010 mg/L needed to control eutrophication

To reach 0.010 mg/L, the phosphorus loading from the point source must be

$$S = C(Q + V_s A) - QC_{in}$$

$$= 0.010(18 + 3.17 \times 10^{-7} \times 90 \times 10^6) - 18 \times 0.010 = 0.29 \text{ g/s}$$

The point source currently applies 0.9 g/s so 67.8 % removal of phosphorus is needed



*Handwritten notes:*  
 $C = (QC_{in} + S) / (Q + V_s A)$   
 $S = C(Q + V_s A) - QC_{in}$   
 $0.9 - 0.29 \rightarrow \frac{0.9 - 0.29}{0.9} \times 100$

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### Problem 2

A phosphorus limited lake with surface area equal to  $90 \times 10^6 \text{ m}^2$  is fed by a  $18 \text{ m}^3/\text{s}$  stream that has a phosphorus concentration of  $0.010 \text{ mg/L}$ . In addition, effluent from a point source adds  $0.9 \text{ g/s}$  of phosphorus. The phosphorus settling rate is estimated as  $10 \text{ m/yr}$ .

a) Estimate the average total phosphorus concentration.

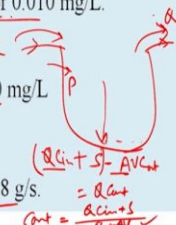
b) What rate of phosphorus removal at the wastewater treatment plant would be required to keep the concentration of phosphorus in the lake at an acceptable level of  $0.010 \text{ mg/L}$ .

**Soln.**

Phosphorus loading from the incoming stream  $QC_{in} = 18.0 \text{ m}^3/\text{s} \times 0.010 \text{ mg/L}$

$$= 18.0 \text{ m}^3/\text{s} \times 0.010 \text{ g/m}^3 = 0.18 \text{ g/s}$$

Adding  $0.9 \text{ g/s}$  from the point source a total phosphorus input rate of  $1.08 \text{ g/s}$ .



*Handwritten notes:*  
 $0.9 + 0.18 = 1.08 \text{ g/s}$   
 $(QC_{in} + S) / (Q + V_s A)$   
 $C_{out} = \frac{QC_{in} + S}{Q + V_s A}$

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So, steady state concentration of the total phosphorus would be

$$C_{out} = (QC_{in} + S) / (Q + V_s A) = 1.08 / (18 + 3.17 \times 10^{-7} \times 90 \times 10^6) \text{ g/m}^3 = 0.023 \text{ mg/L}$$

Which is above  $0.010 \text{ mg/L}$  needed to control eutrophication

To reach  $0.010 \text{ mg/L}$ , the phosphorus loading from the point source must be

$$S = C(Q + V_s A) - QC_{in}$$

$$= 0.010(18 + 3.17 \times 10^{-7} \times 90 \times 10^6) - 18 \times 0.010 = 0.29 \text{ g/s}$$

The point source currently applies 0.9 g/s so 67.8 % removal of phosphorus is needed

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**Problem 3**

CO<sub>2</sub> is emitting from a 80m high industrial chimney of diameter 0.25 m to the atmosphere (1 bar pressure) on a clear summer day. Wind speed at 10m height from the ground is 4 m/s. Calculate the effective stack height. Assume B category stability (p value = 0.15). The stack gas velocity is 8 m/s and the temperature of stack gas and ambient air at 80 m height are 50 °C and 25 °C respectively.

**Solution**

where  $v_s$  = stack flue gas velocity (m/s) ✓  
 $d$  = stack diameter at exit (m) ✓  
 $u$  = wind speed (m/s)  
 $P$  = pressure (k Pa)  
 $T_s$  = stack temperature (flue gases), K  
 $T_a$  = ambient air temperature, K

**Holland's formula** ✓

$$\Delta H = \frac{v_s}{u} d \left[ 1.5 + \left( 2.68 \times 10^{-2} (P) \left( \frac{T_s - T_a}{T_a} \right) d \right) \right]$$

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So, problem 3. CO<sub>2</sub> is emitting from a 80 m high industrial chimney of diameter 0.2 m to the atmosphere, that 1 bar pressure on a clear summer day. Wind speed at 10 m height from the ground is 4 m/s. Calculate the effective stack height. Assume B category stability p value is 0.15. The stack gas velocity is 8 m/s and the temperature of stack gas and ambient air at 80 m height are 50 °C and 25 °C, respectively.

So, these are the given condition. So, we have to calculate the stack height. So, how we can do that? So, we know that Holland's formula

$$\Delta H = \frac{v_s}{u} d \left[ 1.5 + \left( 2.68 \times 10^{-2} (P) \left( \frac{T_s - T_a}{T_a} \right) d \right) \right]$$

Where:  $v_s$  = stack velocity(m/s);  $d$ =stack diameter(m);  $u$ =wind speed(m)  $P$ =Atmospheric pressure (k Pa), mill bars;  $T_s$  = stack gas temperature (K);  $T_a$  = air temperature(K)

$$u_2 = u_1 \left( \frac{z_2}{z_1} \right)^p$$

$$u_2 = 4 \times \left( \frac{80}{10} \right)^{0.15} = 5.464 \frac{m}{s}$$

$$\Delta H = \left( \frac{8 \times 0.25}{5.464} \right) \left[ 1.5 + \left( 2.68 \times 10^{-2} \times 10^2 \times \left( \frac{323 - 298}{323} \right) \times 0.25 \right) \right] = 0.568 \text{ m}$$

Effective stack height = 80 + 0.568 m = 80.568 m

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**Solution**

$$\Delta H = \left( \frac{v_s d}{u} \right) \left[ 1.5 + \left( 2.68 \times 10^{-2} \cdot P \left( \frac{T_s - T_a}{T_s} \right) d \right) \right] \quad \text{and} \quad u_2 = u_1 \left( \frac{z_2}{z_1} \right)^p$$

Where:  
 $v_s$  = stack velocity(m/s); d=stack diameter(m); u=wind speed(m)  
 P=Atmospheric pressure (k Pa), mill bars;  $T_s$  = stack gas temperature (K);  $T_a$  = air temperature(K)

$$u_2 = 4 \times \left( \frac{80}{10} \right)^{0.15} = 5.464 \frac{m}{s}$$

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Effective stack height = 80 + 0.568 m = 80.568 m

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**Problem 3**

CO<sub>2</sub> is emitting from a 80m high industrial chimney of diameter 0.25 m to the atmosphere (1 bar pressure) on a clear summer day. Wind speed at 10m height from the ground is 4 m/s. Calculate the effective stack height. Assume B category stability (p value = 0.15). The stack gas velocity is 8 m/s and the temperature of stack gas and ambient air at 80 m height are 50 °C and 25 °C respectively.

**Solution**

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 d = stack diameter at exit (m)  
 u = wind speed (m/s)  
 P = pressure (k Pa)  
 $T_s$  = stack temperature (flue gases), K  
 $T_a$  = ambient air temperature, K

Holland's formula  $\checkmark$

$$\Delta H = \frac{v_s}{u} d \left[ 1.5 + \left( 2.68 \times 10^{-2} (P) \left( \frac{T_s - T_a}{T_a} \right) d \right) \right]$$

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### Problem 4

A 915 MW power plant with an efficiency of 40 percent uses coal as a fuel source. The coal has 1 percent sulphur content and a calorific value of 30 MJ/kg. The effective stack height is 520 m. If neutral conditions prevail, find out the maximum ground level concentrations of SO<sub>2</sub> at 10 and 100 km from the plant. Assume

(U<sub>10</sub> = 4 m/s, Sulphur = 32, Oxygen = 16, Exponent for velocity, p = 0.16)

$\sigma_y$ (m)	$\sigma_z$ (m)	x (km)
550	140	10
4000	450	100

#### Solution

$$915 \text{ MW} = 915 \times 10^6 \text{ J/S} = 3294 \times 10^3 \text{ MJ/h}$$

$$\text{Coal required} = \frac{3294 \times 10^3}{0.4 \times 30} = 274500 \frac{\text{kg}}{\text{h}} = 274.5 \frac{\text{t}}{\text{h}}$$

Then problem number 4. A 915 MW power plant with an efficiency of 40% uses coal as a fuel source. The coal has 1 % sulphur content and a calorific value of 30 MJ/kg. The effective stack height is 520 m. If neutral conditions prevail, find out the maximum ground water concentrations of SO<sub>2</sub> at 10 and 100 km from the plant.

Assume that U<sub>10</sub> that is wind speed at 10 m height is equal to 4 m/s. Sulphur molecular weight is 32, Oxygen 16. Exponent for velocity is equal to 0.16. And  $\sigma_y$  and  $\sigma_z$  or Sy Sz, we have also discussed in the previous class. And this is our different distance, if you consider the Sy, Sz values are given. So, now, we have to calculate the concentration of the pollutants that is SO<sub>2</sub>.

$$915 \text{ MW} = 915 \times 10^6 \text{ J/S} = 3294 \times 10^3 \text{ MJ/h}$$

$$\text{Coal required} = \frac{3294 \times 10^3}{0.4 \times 30} = 274500 \frac{\text{kg}}{\text{h}} = 274.5 \frac{\text{t}}{\text{h}}$$

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$$SO_2 = 274.5 \times 0.01 \times \left(\frac{64}{32}\right) = 5.49 \frac{t}{h} = 1.5 \frac{kg}{s}$$

$$C(x, y) = \left[ \frac{E}{\pi S_y S_z u} \right] \left[ \exp \left[ -\frac{1}{2} \left( \frac{y}{S_y} \right)^2 \right] \right] \left[ \exp \left[ -\frac{1}{2} \left( \frac{H}{S_z} \right)^2 \right] \right]$$

Where C = concentration at ground level at point (x,y), g/m<sup>3</sup>  
 E = emission rate of pollutant, g/s ✓  
 s<sub>y</sub>, s<sub>z</sub> = plume dispersion standard deviations in horizontal and vertical directions respectively, m  
 u = wind speed at stack effective height H, m/s  
 x = distance down wind, m  
 y = horizontal distance from plume centerline, m  
 H = effective stack height, m

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We can calculate the concentration of SO<sub>2</sub> by using this formula.

$$C(x, y) = \left[ \frac{E}{\pi S_y S_z u} \right] \left[ \exp \left[ -\frac{1}{2} \left( \frac{y}{S_y} \right)^2 \right] \right] \left[ \exp \left[ -\frac{1}{2} \left( \frac{H}{S_z} \right)^2 \right] \right]$$

$$SO_2 = 274.5 \times 0.01 \times \left(\frac{64}{32}\right) = 5.49 \frac{t}{h} = 1.5 \frac{kg}{s}$$

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$$u_2 = u_1 \left( \frac{z_2}{z_1} \right)^p$$

$$u_2 = u_1 \left( \frac{z_2}{z_1} \right)^p = 4 \left( \frac{520}{10} \right)^{0.16} = 7.53 \text{ m/s}$$

$$C_{10,0} = \frac{1.5 \times 10^3}{3.14 \times 550 \times 140 \times 7.53} e^{-\frac{1}{2} \left( \frac{520}{140} \right)^2} = 0.832 \times 10^{-6} \frac{g}{m^3} = 0.832 \frac{\mu g}{m^3}$$

$$C_{100,0} = \frac{1.5 \times 10^3}{3.14 \times 450 \times 4000 \times 7.53} e^{-\frac{1}{2} \left( \frac{520}{450} \right)^2} = 18.08 \times 10^{-6} \frac{g}{m^3} = 18.08 \frac{\mu g}{m^3}$$

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$$SO_2 = 274.5 \times 0.01 \times \left(\frac{64}{32}\right) = 5.49 \frac{t}{h} = 1.5 \frac{kg}{s}$$

$$C(x, y) = \left[ \frac{E}{\pi s_y s_z u} \right] \left[ \exp \left[ -\frac{1}{2} \left( \frac{y}{s_y} \right)^2 \right] \right] \left[ \exp \left[ -\frac{1}{2} \left( \frac{H}{s_z} \right)^2 \right] \right]$$

Where C = concentration at ground level at point (x,y), g/m<sup>3</sup>  
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### Problem 4

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σ <sub>y</sub> (m)	σ <sub>z</sub> (m)	x (km)
550	140	10
4000	450	100

**Solution** ✓  
 915 MW = 915 × 10<sup>6</sup> J/s = 3294 × 10<sup>3</sup> MJ/h  
 Coal required =  $\frac{3294 \times 10^3}{0.4 \times 30} = 244500 \frac{kg}{h} = 274.5 \frac{t}{h}$

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And we need to calculate the value of u<sub>2</sub>

$$u_2 = u_1 \left( \frac{z_2}{z_1} \right)^p$$

$$u_2 = u_1 \left( \frac{z_2}{z_1} \right)^p = 4 \left( \frac{250}{10} \right)^{0.16} = 7.53 \text{ m/s}$$

$$C_{10,0} = \frac{1.5 \times 10^3}{3.14 \times 550 \times 140 \times 7.53} e^{-\frac{1}{2} \left( \frac{520}{140} \right)^2} = 0.832 \times 10^{-6} \frac{g}{m^3} = 0.832 \frac{\mu g}{m^3}$$

$$C_{100,0} = \frac{1.5 \times 10^3}{3.14 \times 450 \times 4000 \times 7.53} e^{-\frac{1}{2} \left( \frac{520}{450} \right)^2} = 18.08 \times 10^{-6} \frac{g}{m^3} = 18.08 \frac{\mu g}{m^3}$$



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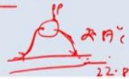
**Problem 5**

A coal fired power plant converts one third of the coals energy into electrical energy. The electrical output of this plant is 500 MW. In this plant only one third of the coal's energy is converted to electrical energy and 90 % of the rest energy of coal is rejected to river through using cooling water drawn from a nearby river and recycling it back to river. The river has a upstream flow of 75 m<sup>3</sup>/s and temperature of 20°C. If the cooling water temperature increases by 5 °C, what flow of cooling water stream is required? What should be the temperature of river water just after receiving the heated cooling water?

**Solution**

Specific heat capacity of water is about 4184 J·kg<sup>-1</sup>·K<sup>-1</sup> at 20 °C

1. Input power =  $3 \times 500 = 1500$  MW
2. Energy lost through water =  $0.9 \times (1500 - 500) = 900$  MW ✓
3. Flow rate of cooling water stream =  $900 \times 10^6 / (4184 \times 5) = 43011$  kg/s = 43.01 m<sup>3</sup>/s
4. Increase in river temperature =  $900 \times 10^6 / (75 \times 10^3 \times 4184) = 2.87$  °C
5. River water temperature after entering the hot cooling water = 22.87 °C



Now, problem number 5. A coal fired power plant converts one third of the coals energy into electrical energy. The electrical output of this plant is 500 MW. In this plant only one third of the coals energy is converted to electrical energy and 90% of the rest energy of coal is rejected to river through using cooling water drawn from a nearby river and recycling it back to river. The river has a upstream flow of 75 m<sup>3</sup>/s and temperature of 20 °C. If the cooling water temperature increases by 5 20 °C, what flow of cooling water stream is required? What should be the temperature of river water just after receiving the heated cooling water?

$$\text{Input power} = 3 \times 500 = 1500 \text{ MW}$$

$$\text{Energy lost through water} = 0.9 \times (1500 - 500) = 900 \text{ MW}$$

Specific heat capacity of water is about 4184 J·kg<sup>-1</sup>·K<sup>-1</sup> at 20 °C

$$\text{Flow rate of cooling water stream} = 900 \times 10^6 / (4184 \times 5) = 43011 \text{ kg/s} = 43.01 \text{ m}^3/\text{s}$$

$$\text{Increase in river temperature} = 900 \times 10^6 / (75 \times 10^3 \times 4184) = 2.87 \text{ }^\circ\text{C}$$

$$\text{River water temperature after entering the hot cooling water} = 22.87 \text{ }^\circ\text{C}$$

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**Problem 6**

Determine carboxyhemoglobin concentration as % saturation for CO concentration of 1200 ppm after 0.5 h of exposure? Further, determine the minimum time for 80% saturation.

**Solution:**

$\% \text{COHb} = \beta(1 - e^{-\gamma t}) (\text{CO})$

Where, %COHb = Carboxyhemoglobin as % saturation;  
CO = Carbon monoxide conc. in ppm;  
 $\gamma = 0.402 \text{ h}^{-1}$ ;  $\beta = 0.15 \text{ \%/ ppm CO}$ ; and  
t = exposure time in hours

Part (a): %COHb=32.78;      Part (b): Time=1.46 h.

Now, problem number 6. Determine carboxyhemoglobin concentration as percentage saturation for carbon monoxide concentration of 1200 ppm after 0.5 h of exposure. Further, determine the minimum time for 80% saturation. So, we know some empirical relationship to find out the concentration of carboxyhemoglobin in the blood.

$$\% \text{COHb} = \beta(1 - e^{-\gamma t}) (\text{CO})$$

Where, %COHb = Carboxyhemoglobin as % saturation;

CO = Carbon monoxide conc. in ppm;

$\gamma = 0.402 \text{ h}^{-1}$ ;  $\beta = 0.15 \text{ \%/ ppm CO}$ ; and

t = exposure time in hours

Part (a): %COHb=32.78;      Part (b): Time=1.46 h.

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**Problem 7**

Find out the air-to-fuel ratio (m/m) required for complete combustion of a liquid fuel (average formula  $C_7H_{13}$ ) in an internal combustion engine.

**Solution**

$$C_7H_{13} + 10.25 O_2 + (78/21) * 10.25 N_2 = 7CO_2 + 6.5 H_2O + 38.07 N_2$$
$$C_7H_{13} = 97 \text{ g}; \quad 10.25 O_2 = 328 \text{ g}; \quad 38.07 N_2 = 1066 \text{ g}$$
$$\text{Air/ fuel} = (1066 + 328) / 97 = 14.37$$

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Now, problem number 7. Find out the air to fuel ratio required for complete combustion of a liquid fuel (average formula  $C_7 H_{13}$ ) in an internal combustion engine.



$$C_7H_{13} = 97 \text{ g}; \quad 10.25 O_2 = 328 \text{ g}; \quad 38.07 N_2 = 1066 \text{ g}$$

$$\text{Air/ fuel} = (1066 + 328) / 97 = 14.37$$

Thank you very much for your patience.