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Basic process engineering concepts

Prof Kevin Harding

kevin.harding@wits.ac.za



Units of Measurement

Concentration of toxic measured in ppm or ppb. Energy typically measured in Gigawatts

Liquids:

Conc. of substances dissolved in water is expressed in terms of mass or number per unit volume of mixture (mg/micrograms, or moles per litre of mixture).

- Conversion of mg/L to ppm: $1 \text{ mg/L} = 1 \text{ g/m}^3 = 1 \text{ ppm}$ (by weight)
- $1 \text{ ug/L} = 1 \text{ ppb}$ (by weight)
- $1 \text{ mg/L} = \text{ppm (by weight)} \times \text{specific gravity of mixture}$

Gases:

For air pollution, concentrations in volumetric terms

- $(1 \text{ volume of gaseous pollutant}) / (10^6 \text{ volumes of air}) = 1 \text{ ppm}$ (by volume) = 1ppmv
- **At 0° C & 1 atm:** $1 \text{ mg/m}^3 = (1 \text{ ppmv} \times \text{mol wt}) / 22.414$
- **At 25° C & 1 atm:** $1 \text{ mg/m}^3 = (1 \text{ ppmv} \times \text{mol wt}) / 24.465$
- **In general:** $1 \text{ mg/m}^3 = [(1 \text{ ppmv} \times \text{mol wt}) / 22.414] \times [273.15 \text{K} / \text{T(K)}] \times [\text{P(atm)} / 1 \text{ atm}]$

Examples: *Units of Measurement*

Example 1

Find the volume that 1 mole of ideal gas would occupy at STP of 1 atm & 0°C. Repeat the calculation at 1 atm & 25°C.

Example 2

The South African Air Quality Standard for carbon monoxide (based on 8-hour measurement) is 9.0 ppmv. Express this as a % by volume as well as in mg/m³ at 1 atm & 25°C.

The image shows the silhouettes of several wind turbines against a vibrant sunset sky. The sky transitions from a deep purple at the top to a bright orange and yellow near the horizon, with some dark clouds visible. The turbines are positioned on the left side of the frame, with their blades extending across the sky.

Conservation of mass & energy

Conservation of Mass: Tool for quantitatively tracking pollutants as they disperse in to the environment

- mass of carrying fluid (air or water)
- mass of carried contaminant, e.g., Mercury
- mass of a relevant quantity, e.g., dissolved oxygen

Conservation of Energy: Accounting tool for energy

- Total energy (mechanical + thermal)
- Usually thermal energy dominates

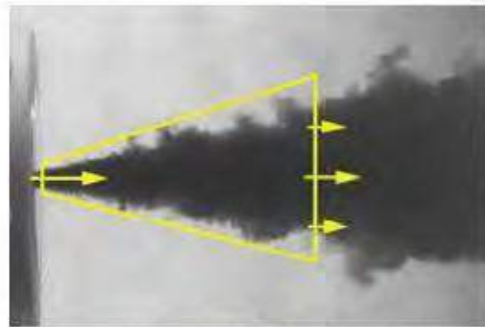
Material Balance

$$\frac{dM}{dt} = \sum_{i=0}^n m_i$$

for each stream i , where m is positive for inlet and negative for outlet streams



Dartmouth College smokestack
Cone around a smokestack plume



Turbulent jet in fluids lab at Trayer School
Section of a discharge jet



White River, Vermont
Section of a river



Ferguson Lake, British Columbia, Canada
An entire lake

Examples:

Dissolved solids in body of water, heavy metals in solids, CO₂ in the air, radio active radon gas at home/office, decomposing wastes in lake.

Material Balance Systems (1)

1. Steady state system:

$$\frac{dM}{dt} = \sum_{i=0}^n m_i$$

$$0 = m_{in} - m_{out}$$

$$m_{in} = m_{out}$$

Material Balance Systems (2)

2. Batch system with non-conservative pollutants (Bacterial concentration in a closed water storage tank, CO₂ in poor ventilated room increases as we breath)

By a mole balance on a single species (A):

Final = Initial + Change

moles of A $\big|_{t+\Delta t}$ = moles of A $\big|_t$ + moles of A reacted during Δt

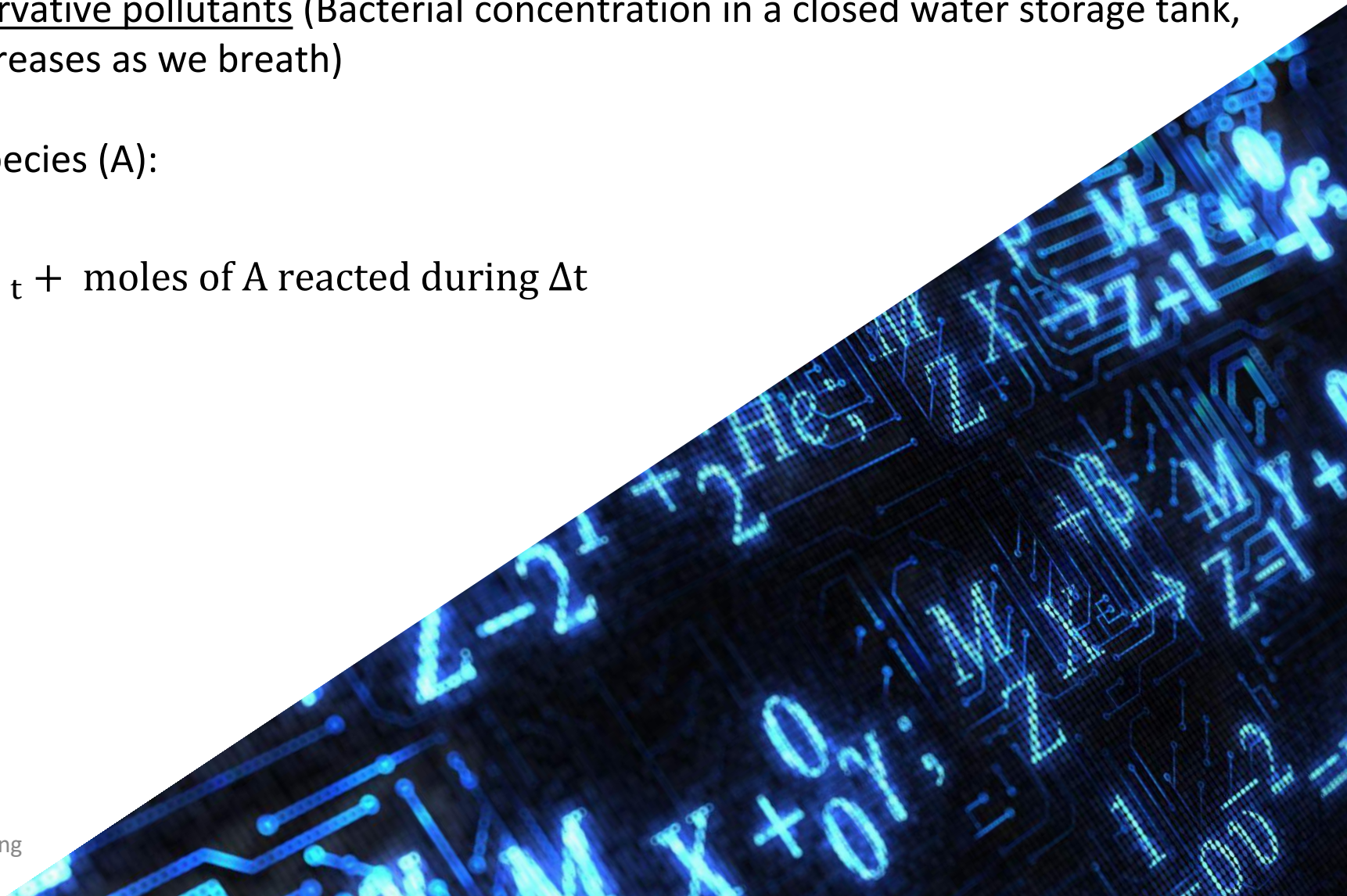
$$N_A \big|_{t+\Delta t} = N_A \big|_t + r_A \Delta t \cdot V$$

Solving:

$$\frac{N_A \big|_{t+\Delta t} - N_A \big|_t}{\Delta t} = r_A \cdot V$$

Taking limit $\Delta t \rightarrow 0$:

$$\frac{dN_A}{dt} = r_A \cdot V$$



Material Balance Systems (2)

$$\frac{dN_A}{dt} = r_A \cdot V$$

But:

$$C_A = \frac{N_A}{V} \text{ or } N_A = C_A \cdot V$$

Substitute for N_A

$$\frac{d(C_A \cdot V)}{dt} = r_A \cdot V$$

If density and volume are constant

$$\frac{dC_A}{dt} = r_A$$

Material Balance Systems (2)

For a zero-order reaction (water evaporation)

$$\frac{dC_A}{dt} = r_A$$

$$\frac{dC_A}{dt} = -k$$

$$dC_A = -k dt$$

$$\int dC_A = -k \int dt$$

$$C - C_0 = -kt$$

Material Balance Systems (2)

For a first-order reaction (radioactive decay)

$$\frac{dC_A}{dt} = r_A$$

$$\frac{dC_A}{dt} = -k \cdot C_A$$

$$\frac{dC_A}{C_A} = -k \cdot dt$$

$$\int \frac{dC_A}{C_A} = -k \int dt$$

$$\ln \frac{C}{C_0} = -kt \quad \text{OR} \quad C = C_0 e^{-kt}$$

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Material Balance Systems (2)

For a second-order reaction (hydroxyl radical reactions with volatile pollutants)

$$\frac{dC_A}{dt} = r_A$$

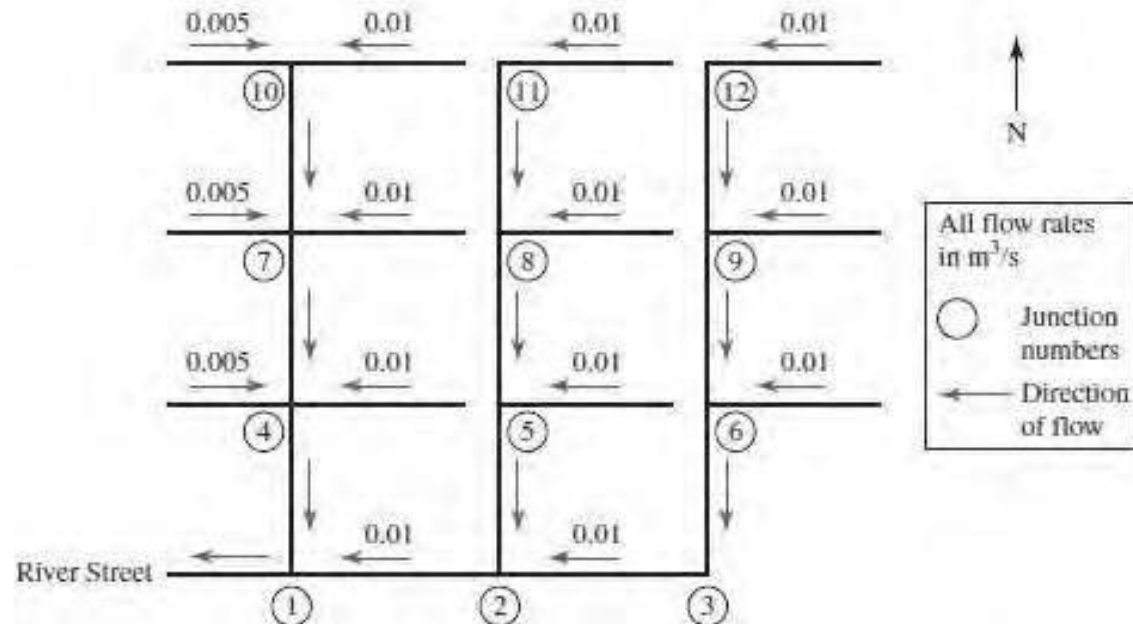
$$\frac{dC_A}{dt} = -k \cdot C_A^2$$

$$\int \frac{dC_A}{C_A^2} = -k \int dt$$

$$C = \frac{C_0}{1 + C_0 k \cdot t}$$

Examples: Material Balance Systems

Example 2-3. A storm sewer network in a small residential subdivision is shown in the following sketch. The storm water flows by gravity in the direction shown by the pipes. Storm water only enters the storm sewer on the east–west legs of pipe. No storm water enters on the north–south legs. The flow rate for each section of pipe is also shown by each section of pipe. The capacity of each pipe is $0.120 \text{ m}^3/\text{s}$. During large rain storms, River Street floods below junction number 1 because the flow of water exceeds the capacity of the storm sewer pipe. To alleviate this problem and to provide extra capacity for expansion, it is proposed to build a retention pond to hold the storm water until the storm is over and then gradually release it. Where in the pipe network should the retention pond be built to provide approximately 50 percent extra capacity ($0.06 \text{ m}^3/\text{s}$) in the remaining system?



Examples: *Material Balance Systems*

Example 2-4. The air pollution control equipment on a municipal waste incinerator includes a fabric filter particle collector (known as a baghouse). The baghouse contains 424 cloth bags arranged in parallel, that is $1/424$ of the flow goes through each bag. The gas flow rate into and out of the baghouse is $47 \text{ m}^3/\text{s}$, and the concentration of particles entering the baghouse is $15 \text{ g}/\text{m}^3$. In normal operation the baghouse particulate discharge meets the regulatory limit of $24 \text{ mg}/\text{m}^3$. During preventive maintenance replacement of the bags, one bag is inadvertently not replaced, so only 423 bags are in place.

Calculate the fraction of particulate matter removed and the efficiency of particulate removal when all 424 bags are in place and the emissions comply with the regulatory requirements. Estimate the mass emission rate when one of the bags is missing and recalculate the efficiency of the baghouse. Assume the efficiency for each individual bag is the same as the overall efficiency for the baghouse.

Material Balance Systems (3)

3. Steady-state system with non-conservative pollutants (water in a shallow pond with inlet and outlet, air in a well-ventilated room)

From the previous derivation:

$$\frac{dN_A}{dt} = r_A \cdot V$$

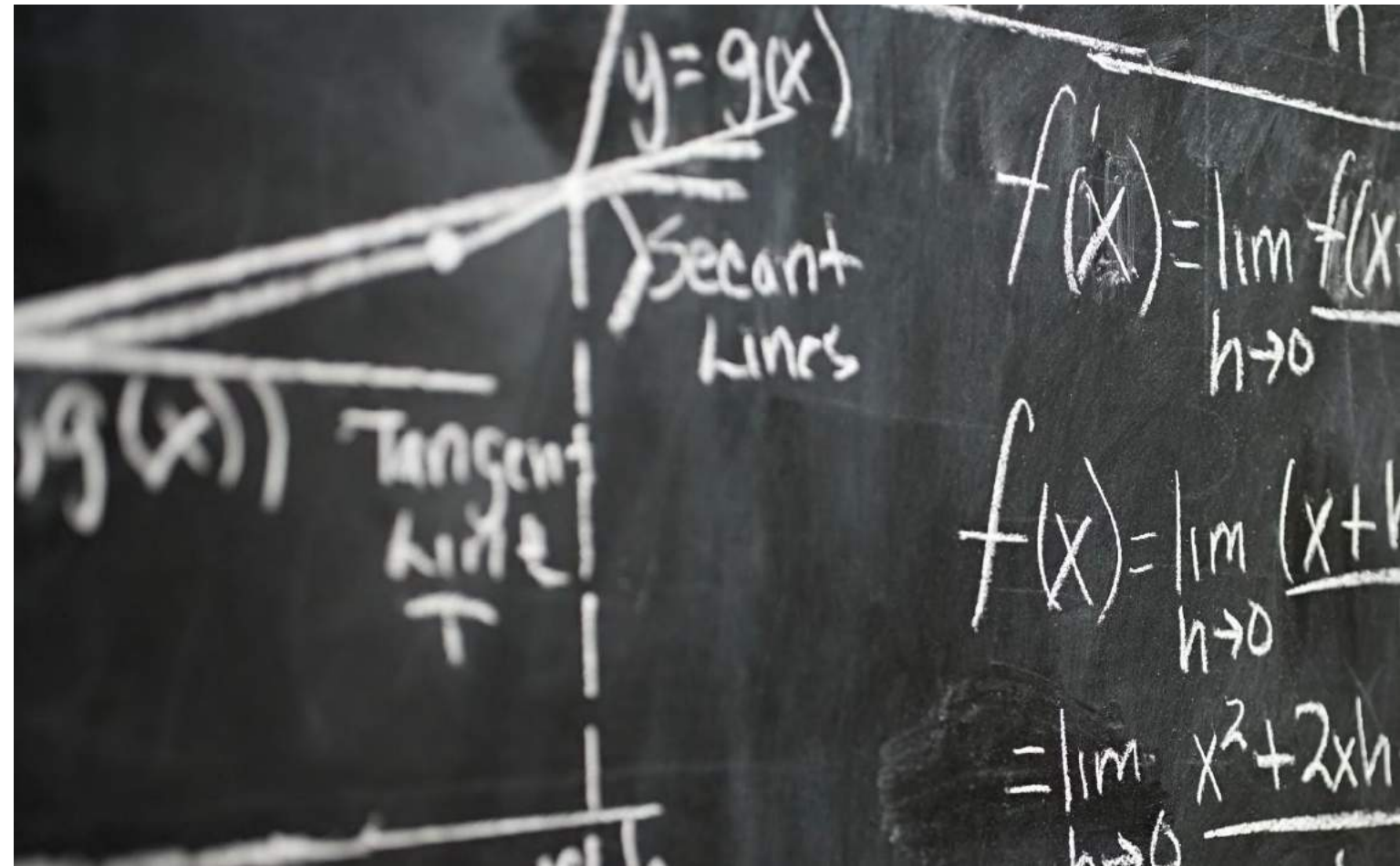
For steady state: "d/dt" is zero

$$0 = r_A \cdot V$$

Zero order: $0 = -k \cdot V$

First order: $0 = -k \cdot C \cdot V$

Second order: $0 = -k \cdot C^2 \cdot V$



Material Balance Systems (4)

4. Plug flow reactors (flow of water in a river)

From a differential balance:

(Moles of A in at V) = (Moles of A out at V + ΔV) – (moles of A reacted)

$$\dot{N}_A|_V = \dot{N}_A|_{V+\Delta V} - r_A \Delta V$$

$$\frac{\dot{N}_A|_{V+\Delta V} - \dot{N}_A|_V}{\Delta V} = r_A$$

Taking the limits:

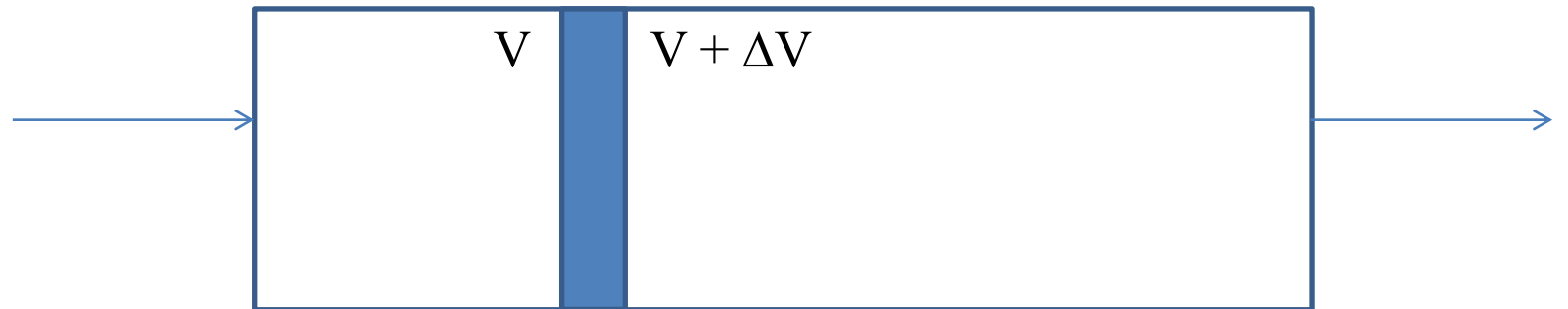
$$\frac{d\dot{N}_A}{dV} = r_A$$

Zero order: $C = C_0 - k \cdot t$

First order: $C = C_0^{-kt}$

Second order: $C = \frac{C_0}{1+C_0 k \cdot t}$

Where t is the residence time, given by $t = V/Q$



Examples: *Material Balance Systems*

Example 2-7. A wastewater treatment plant must disinfect its effluent before discharging the wastewater to a near-by stream. The wastewater contains 4.5×10^5 fecal coliform colony-forming units (CFU) per liter. The maximum permissible fecal coliform concentration that may be discharged is 2,000 fecal coliform CFU/L. It is proposed that a pipe carrying the wastewater be used for disinfection process. Determine the

length of pipe required if the linear velocity of the wastewater in the pipe is 0.75 m/s. Assume that the pipe behaves as a steady-state plug-flow system and that the reaction rate constant for destruction of the fecal coliforms is 0.23 min^{-1} .

Material Balance Systems (5)

4. Step change functions (pollutant added in a river)

This can be modelled as a CSTR:

$$V \frac{dC}{dt} = Q \cdot C_i - QC - k_d V \cdot C + k_g V$$

Where:

V = Volume (m^3)

C = Inside concentration and exiting waste stream concentration (g/m^3)

C_i = concentration of the pollutants entering (g/m^3)

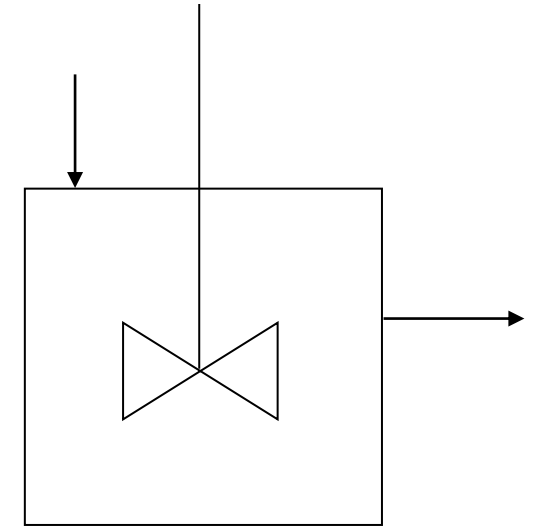
Q = the total flowrate in and out of system (m^3/hr)

k_d = decay rate (hr^{-1})

k_g = production rate ($g \cdot m^{-3} \cdot hr^{-1}$)

At steady state:

$$C_{infinity} = \frac{(Q \cdot C_i + k_g V)}{Q + k_d V} \text{ AND } C(t) = C_{infinity} + (C_0 - C_{infinity}) \exp\left(-t \left(k_d + \frac{Q}{V}\right)\right)$$



Examples: *Mass transfer*

Example 1

A stream flowing at $10 \text{ m}^3/\text{s}$ has a tributary feeding into it with flow of $5.0 \text{ m}^3/\text{s}$. The stream's concentration of chloride upstream of the junction is 20.0 mg/L , and the tributary concentration chloride is 40.0 mg/L . Find the downstream chloride concentrations. State your assumptions. Assume complete mixing and no reaction.

Example 2

Consider a $10 \times 10^6 \text{ m}^3$ lake fed by a polluted stream having a flow rate of $5.0 \text{ m}^3/\text{s}$ and pollutant concentration equal to 10.0 mg/L . There is also sewage outfall that discharges $0.5 \text{ m}^3/\text{s}$ of waste water having a pollutant concentration of 100 mg/L . The stream and sewage wastes have decay rate coefficient of $0.2/\text{day}$. Assuming the pollutant is completely mixed in the lake and assuming no evaporation or other water losses or gains, find the steady state pollutant concentration in the lake.

Example 3

A bar with a volume of 500 m^3 has 95 smokers in it, each smoking 4 cigarettes per hour. An individual cigarette emits, among other things, about 1.4 mg of formaldehyde (HCHO). Formaldehyde is converted to CO_2 with a reaction rate coefficient $k = 0.4/\text{h}$. Fresh air enters the bar at a rate of $700 \text{ m}^3/\text{h}$, and stale air leaves at the same rate. Assuming complete mixing, estimate the steady-state concentration of formaldehyde in the air. At 25°C and 1 atm of pressure, how does the result compare with threshold for eye irritation of about 0.05 ppm ?

Examples:

Mass transfer

Example 4

Suppose the bar in the previous example opens at 5PM, the air is clean. If formaldehyde, with decay rate $k_d = 0.4/\text{hr}$, is emitted from cigarette smoke at the constant rate of 140 mg/hr starting at 5PM., what would be the concentration at 6PM?

Example 5

Every year, herons, seagulls, eagles, and other birds mass along a 4.75 km stretch of stream connecting a lake to the ocean to catch the fingerling salmon as they migrate downstream to the sea. The birds are efficient fishermen and will consume 10,000 fingerlings per kilometer of stream each hour regardless of the number of the salmon in the stream. The average stream cross-sectional area is 20m^2 , and the salmon move downstream with the stream's flowrate of $700\text{ m}^3/\text{min}$. If there are 7 fingerlings per m^3 in the water entering the stream, what is the concentration of the salmon that reach the ocean when the birds are feeding? Assume plug flow reactor model for the lake.

Example 6

Consider the $10 \times 10^6\text{ m}^3$ lake analyzed previously which, under the conditions given, was found to have a steady state pollution of 3.5 mg/L. The pollution concentration is non-conservative with reaction-rate constant $k_d = 0.2/\text{day}$. Suppose the condition of the lake is deemed unacceptable. To solve the problem, it is decided to divert the sewage outfall from the lake, eliminating it as a source of pollution. The incoming stream still has flow $Q_s = 5.0\text{ m}^3/\text{s}$ and concentration $C_s = 10.0\text{ mg/L}$. With the sewage outfall removed, the outgoing flow Q is also $5.0\text{ m}^3/\text{s}$. Assuming complete mix conditions, find the concentration if the pollutant in the lake one week after the diversion, and find the new final steady state concentration.



Energy Balance

Thermodynamics accounts for energy (loss/waste) in the the environment

- Heat: Transfer of between objects of different temperatures.
- Energy: Ability to do work
- Work: Measure of energy when an object moves
- Power: Energy transferred per unit time



Energy Transfer

0th Law: If 2 thermodynamic systems are each in thermal equilibrium with a 3rd system, then they are in thermal equilibrium with each other

1st Law (Conservation of energy): Energy can neither be created nor destroyed, but it can be changed from one form to another

2nd Law (there is always inefficiency): Entropy in an isolated system always increases. Any isolated system spontaneously evolves towards thermal equilibrium—the state of maximum entropy of the system.

3rd Law: The entropy of a system approaches a constant value as its temperature approaches absolute zero

Energy Balance – conservation of energy

$$\frac{d(U + E_k + E_p)}{dt} = \sum_{i=1}^n (H_i + E_k + E_p) + \dot{Q} + \dot{W} + \dot{W}_{PV}$$

For thermal systems, this is more commonly simplified to:

$$\frac{dU}{dt} = \sum_{i=1}^n H_i + \dot{Q} + \dot{W}$$

For mechanical systems (single input, single output system), this is simplified to:

$$\left(mgz + \frac{1}{2} (mv^2) \right)_{\text{out}} + \Phi = \left(mgz + \frac{1}{2} (mv^2) \right)_{\text{in}} - m \int_{P,\text{in}}^{P,\text{out}} \frac{dP}{\rho} + \dot{W}_s$$



Heat Transfer

Conduction:

$$\dot{q} = -k \cdot A \frac{dT}{dx}$$

\dot{q} : Heat Flow (W)

k: Thermal conductivity (W/(m.K))

A: Area perpendicular to heat flow (m²)

T: Temperature (K)

x: Direction in which heat flows (m)



Heat Transfer

Convection:

$$\dot{q} = hA(T_s - T_b)$$

\dot{q} : Heat Flow (W)

h : Heat transfer coefficient (W/(m².K))

A : Area perpendicular to heat flow (m²)

T_s : Surface temperature (K)

T_b : Bulk temperature (K)



Heat Transfer

Radiation:

$$\dot{q} = A\sigma T^4$$

\dot{q} : Heat Flux (W)

A: Cross Sectional Area (m²)

σ : Stefan Boltzmann Constant = $5.67 \times 10^{-8} \text{ W.m}^{-2}\text{K}^{-4} = \frac{2\pi^5 k_B^4}{15h^3 c^2}$

k_B = Boltzmann constant – $1.38 \times 10^{-23} \text{ J/K}$;

h = Plank constant – $6.626 \times 10^{-34} \text{ J.s}$

c = speed of light m/s

T = Temperature (K)



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Kevin Harding