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Course Name: Introduction to Environmental Engineering and Science – Fundamentals and Sustainability Concepts

Faculty Name: Dr. Brajesh Kumar Dubey

Department : Civil engineering

Topic Physical Process in Environment

Lecture 16: Mass Balances and Batch reactor

CONCEPTS COVERED

Concepts to be Covered

- Physical Process in Environment

Mass Balances

- Law of conservation of mass

"Mass can neither be produced nor destroyed"

Commonly used in: Mass balance and energy balance

Mass at time t + Δt = mass at time t

+ (mass entering from to t + Δt)

- (mass exiting from t to t + Δt)

+ (net mass of chemical produced from other compounds by reactions between t and t + Δt)

Mass Balances

- **Mass flux**

The rate at which mass enters and leaves the system.

$$\frac{Mass\ at\ time\ t+\Delta t - mass\ at\ time\ t}{\Delta t} = \frac{mass\ entering\ from\ to\ t+\Delta t}{\Delta t} - \frac{mass\ exiting\ from\ t\ to\ t+\Delta t}{\Delta t} + \frac{net\ mass\ of\ chemical\ produced\ from\ othe\ compounds\ by\ reactions\ between\ t\ and\ t+\Delta t}{\Delta t}$$

Mass Balances

Mass flux

- The rate at which mass enters and leaves the system.

When $\Delta t \longrightarrow 0$

(mass accumulation rate) = (mass flux in) – (mass flux out)

+ (Net rate of chemical production)

$$\boxed{\frac{dm}{dt} = \acute{m}_{in} - \acute{m}_{out} + \acute{m}_{reaction}}$$

ḿ = mass flux with units of mass/time

Mass Balances

Control volume

- A mass balance is useful only in terms of a specific region of space, which has boundaries across which the terms $\acute{m}_{in}$ and $\acute{m}_{out}$ are determined. This region is called control volume.
- Theoretically volume of any shape and location can be used as control volume. The most important attribute of a control volume is that it has boundaries over which $\acute{m}_{in}$ and $\acute{m}_{out}$ can be calculated.

Reactor design

Mode of operation

1. Batch reactor/ Completely mixed batch reactor (CMBR)

2. Continuous reactor/continuous stirred tank reactor (CSTR)

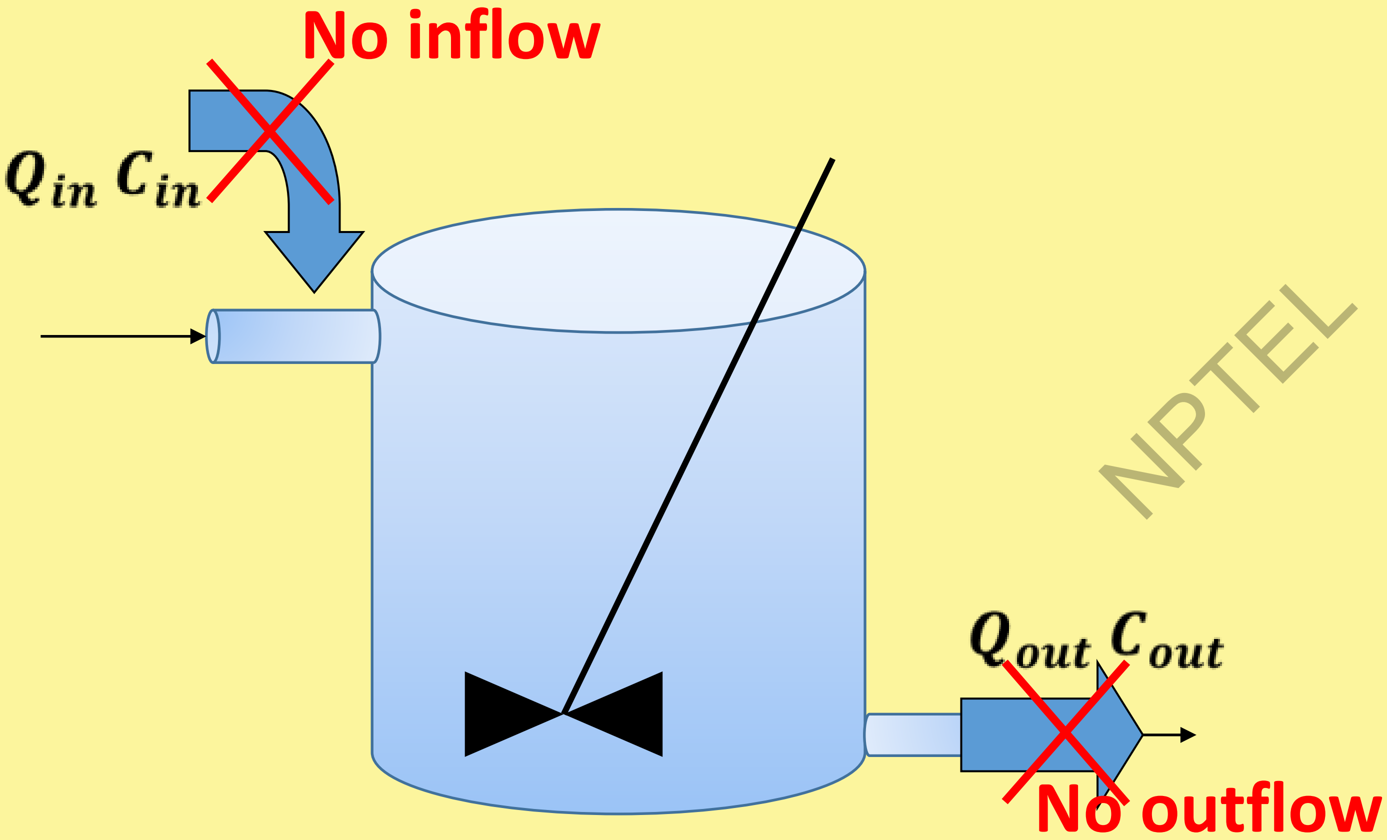
3. Plug flow reactor

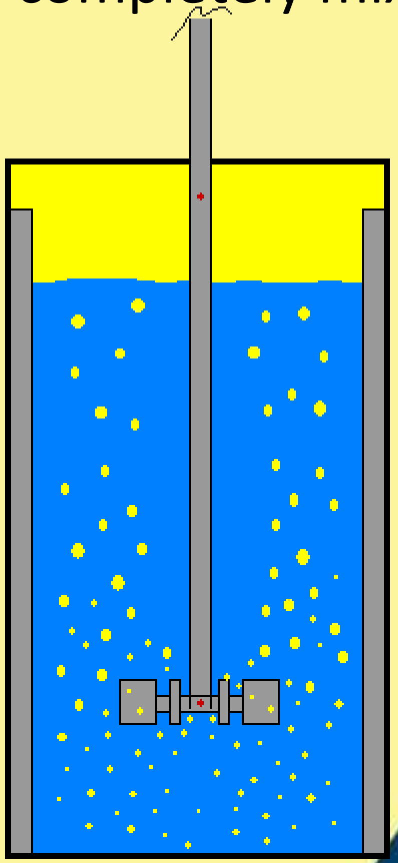
Reactor kinetics

1. Reaction order zero
2. First order reaction
3. Second order reaction

Batch reactor/ Completely mixed batch reactor (CMBR)

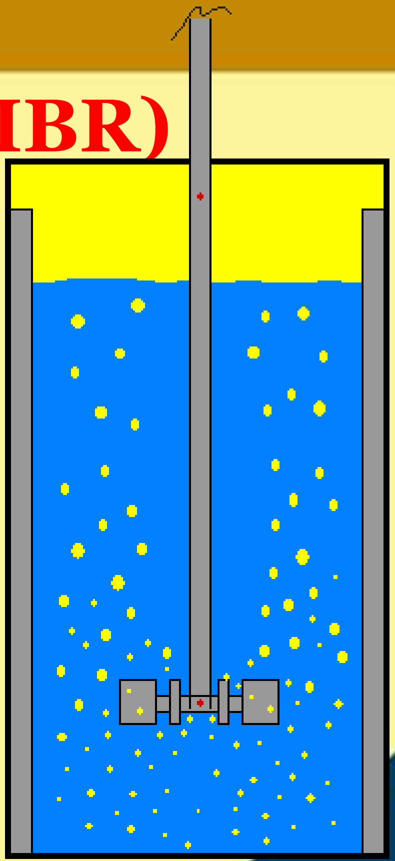
Stir bar is used as a symbol to indicate the reactor is completely mixed





Schematic diagram of complete batch reactor

Batch reactor/ Completely mixed batch reactor (CMBR)



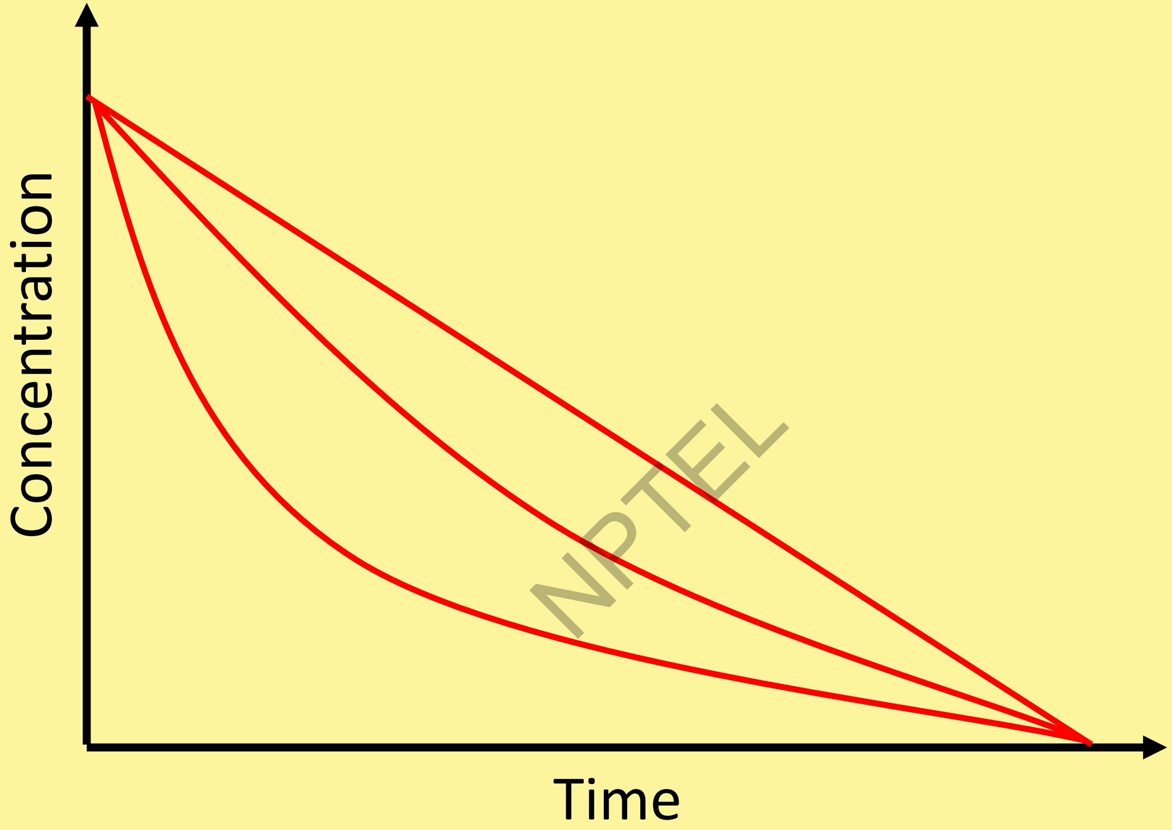
Batch reactors are used in a number of industries producing small quantities of high-valued materials such as cell cultivation,

polymer synthesis

and crystallization.

To operate the batch reactor with success, the final quality performance has to maintain with minimum cost. Though operated with the same recipe, the batch process shows batch-to-batch variations in its specified trajectories. Therefore, online process monitoring is essential to achieve successful batch operation.

Batch reactor/ Completely mixed batch reactor (CMBR)



Batch reactor/ Completely mixed batch reactor (CMBR)

- The simplest reactor type
- Flow is neither entering nor leaving the reactor
- The liquid contents are mixed completely and uniformly

Batch reactor/ Completely mixed batch reactor (CMBR)

Applications:

- Is a non-continuous and perfectly mixed closed vessel where a reaction takes place.
- A common use of batch reactors in laboratories is to determine the reaction equation

  and rate constant for a chemical reaction.
- The kinetic information determined in a batch reactor can be used to

  design other types of reactors and full-scale treatment facilities.

Batch reactor/ Completely mixed batch reactor (CMBR): Reaction order zero

Fundamental equation of mass balance in CMBR $\frac{dm}{dt} = \acute{m}_{in} - \acute{m}_{out} + \acute{m}_{reaction}$

For batch reactor have no inputs or outputs

$$\acute{m}_{in} - \acute{m}_{out} = 0$$

$$\frac{dm}{dt}_{net} = \frac{dm}{dt}_{reaction}$$

For zero order reaction $\frac{dm}{dt}_{net}$ = -k

$$\int_{C_0}^{C_e} dc = \int_0^t -k\, dt$$

$[C_e - C_0]$ = -kt

$C_e = C_0$-kt

Batch reactor/ Completely mixed batch reactor (CMBR): First order reaction

$$\frac{dm}{dt} = \acute{m}_{in} - \acute{m}_{out} + \acute{m}_{reaction}$$

For batch reactor have no inputs or outputs

$$\acute{m}_{in} - \acute{m}_{out} = 0$$

$$\frac{dm}{dt}_{net} = \frac{dm}{dt}_{reaction}$$

For zero order reaction $\frac{dm}{dt}_{net}$ = -kc

$$\int_{C_0}^{C_e} \frac{dc}{c} = \int_0^t -k\, dt$$

$$ln(C_e/C_0) = -kt$$

$$C_e = C_0\, e^{-kt}$$

Batch reactor/ Completely mixed batch reactor (CMBR): Second order reaction

$$\frac{dm}{dt} = \acute{m}_{in} - \acute{m}_{out} + \acute{m}_{reaction}$$

For batch reactor have no inputs or outputs

$$\acute{m}_{in} - \acute{m}_{out} = 0$$

$$\frac{dm}{dt}_{net} = \frac{dm}{dt}_{reaction}$$

For zero order reaction $\frac{dm}{dt}_{net}$ = -kC^2

$$\int_{C_0}^{C_e} \frac{dc}{C^2} = \int_0^t -k\,dt$$

$$\frac{1}{C_e} = \frac{1}{C_0} + kt$$

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Thank you

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Course Name: Introduction to Environmental Engineering and Science – Fundamentals and Sustainability Concepts

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Topic Physical Process in Environment

Lecture 17: Mass balance in Continuous reactor/continuous stirred tank reactor (CSTR) and plug flow reactor

Reactor design

Mode of operation

1. ~~Batch reactor/ Completely mixed batch reactor (CMBR)~~
2. Continuous reactor/continuous stirred tank reactor (CSTR)
3. Plug flow reactor

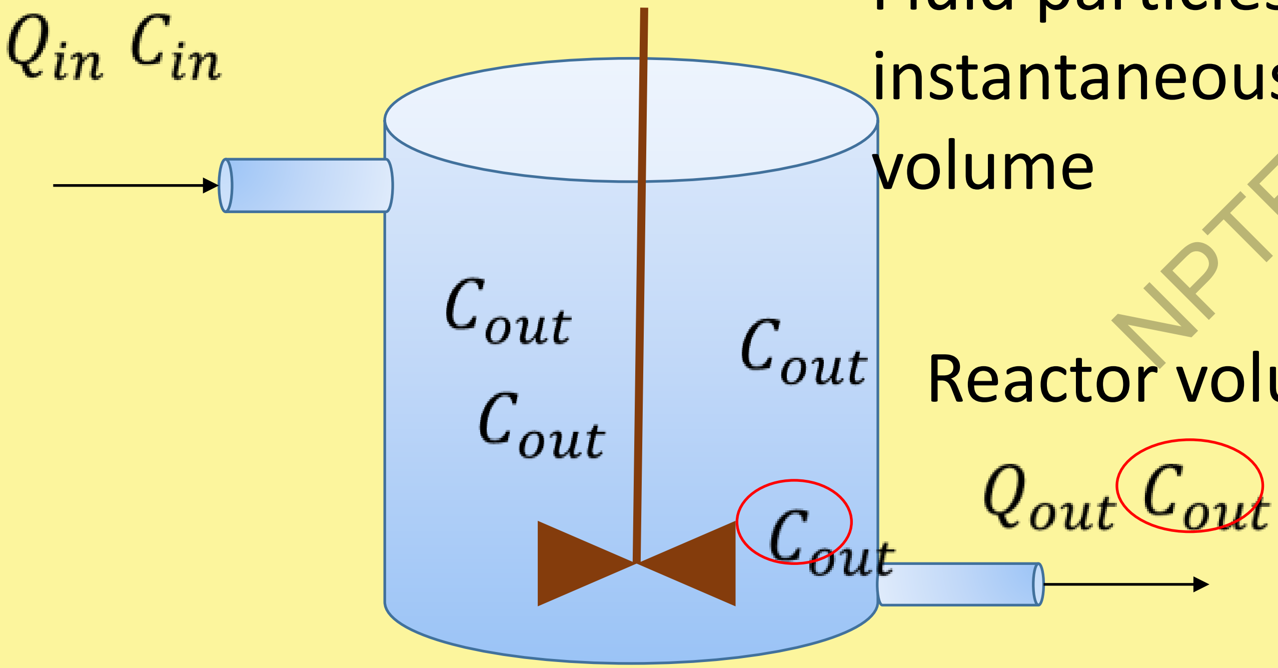
Reactor kinetics

1. Reaction order zero
2. First order reaction
3. Second order reaction

Continuous stirred tank reactor (CSTR)

Stir bar is used as a symbol to indicate the reactor is completely mixed

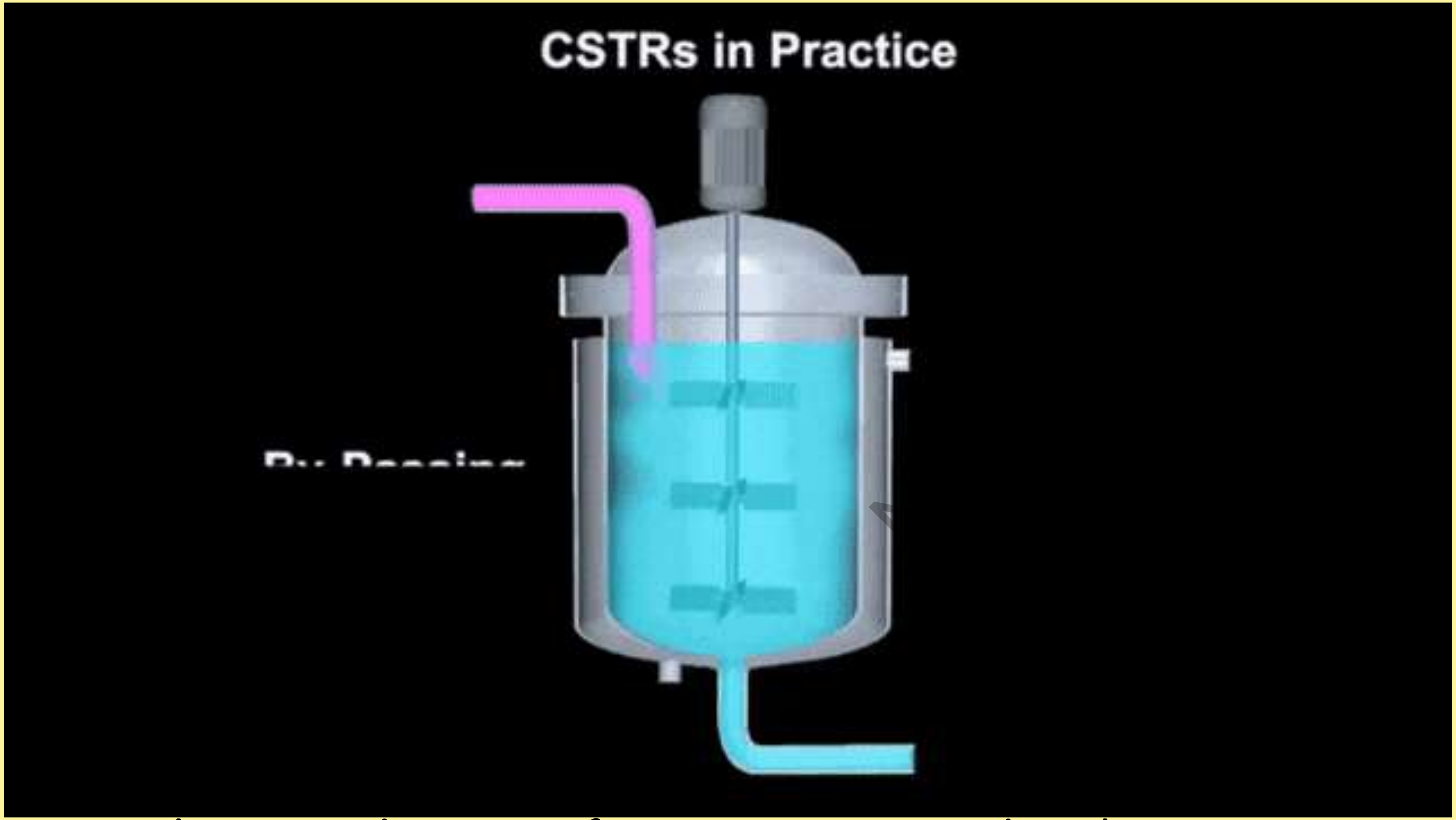
Fluid particles that enter the reactor are instantaneously dispersed throughout the reactor volume



Reactor volume = V

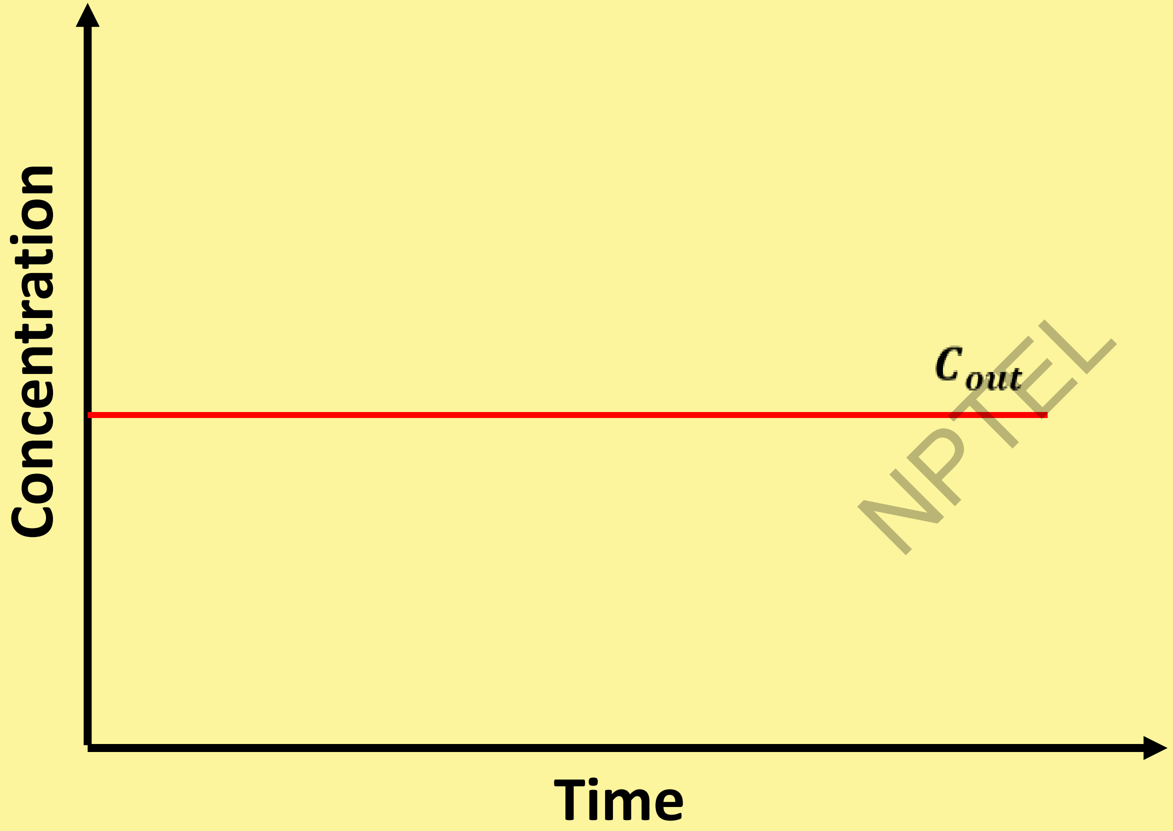
Schematic diagram of continuous stirred tank reactor

Continuous stirred tank reactor (CSTR)



Schematic diagram of continuous stirred tank reactor

Continuous stirred tank reactor (CSTR)



Mass Balances

The following discussion describes each term in a mass balance of a compound within CSTR

Mass accumulation rate (dm/dt)

The rate of change of mass within a control volume, dm/dt, is referred to as the mass accumulation rate.

To directly measure the mass accumulation rate would require determining the total mass within the control volume of the compound for which the mass balance is being

conducted.

Continuous stirred tank reactor (CSTR)

$$\frac{dm}{dt} = \acute{m}_{in} - \acute{m}_{out} + \acute{m}_{reaction}$$

$$\left(\frac{dm}{dt}\right)_{net} V = \acute{m}_{in} - \acute{m}_{out} + \left(\frac{dm}{dt}\right)_{reaction} V$$

at steady state $\left(\frac{dm}{dt}\right)_{net} = 0$

$$0 = \acute{m}_{in} - \acute{m}_{out} + \left(\frac{dm}{dt}\right)_{reaction} V$$

Continuous stirred tank reactor (CSTR): Zero order reaction

$$0 = \acute{m}_{in} - \acute{m}_{out} + \left(\frac{dm}{dt}\right)_{reaction} V$$

$$\acute{m}_{in} = QC_0$$

$$\acute{m}_{in} = QC_{out}$$

For zero order reaction $\frac{dm}{dt}_{net}$ = -k

$$0 = QC_0 - QC_{out} - kV$$

$$QC_0 - QC_{out} = kV$$

$$C_{out} = C_0 - kV/Q$$

Continuous stirred tank reactor (CSTR): First order reaction

$$0 = \acute{m}_{in} - \acute{m}_{out} + \left(\frac{dm}{dt}\right)_{reaction} V$$

$$\acute{m}_{in} = QC_0$$

$$\acute{m}_{in} = QC_{out}$$

For zero order reaction $\frac{dm}{dt}_{net}$ = $-kC_{out}$

$$0 = QC_0 - QC_{out} - kC_{out}V$$

$$QC_0 - QC_{out} = kC_{out}V$$

$$C_0 = C_{out} + kC_{out}V/Q$$

$$C_{out} = C_0 /(1 + \frac{kV}{Q})$$

Continuous stirred tank reactor (CSTR): Second order reaction

$$0 = \acute{m}_{in} - \acute{m}_{out} + (\frac{dm}{dt})_{reaction} \text{V}$$

$$\acute{m}_{in} = QC_0$$

$$\acute{m}_{in} = QC_{out}$$

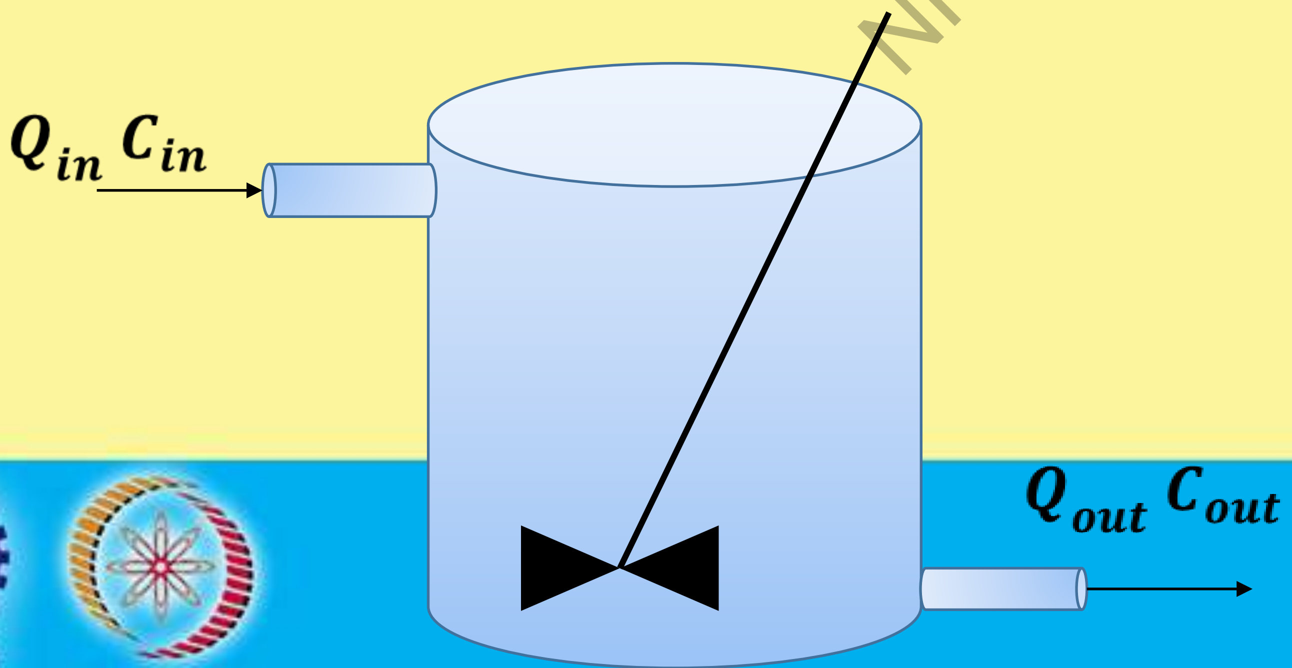
For zero order reaction $\frac{dm}{dt}_{net}$ = -kC_{out}^2

$$0 = QC_0 - QC_{out} - kC_{out}^2 V$$

Solve this equation for C_{out} ... Homework!!!!!!

Example: 1

The CMBR shown in Figure below is used to treat an industrial waste, using a reaction that destroys the pollutant according to first-order kinetics, with k=0.216/day. The reactor volume is 500 m^3, the volumetric flow rate of the single inlet and exit is 50 m^3/day, and the inlet pollutant concentration is 100 mg/L. What is the outlet concentration after treatment?



An obvious control volume is the tank itself. The problem requests a single, constant outlet concentration, and all problem conditions are constant. Therefore, this is a steady-state problem $(dm/dt) = 0$.

The mass balance equation with a first-order decay term

$\left([dC/dt]_{reaction\ only} = -kc \text{ and } m_{rxn} = -Vkc\right)$ is:

$$\frac{dm}{dt} = m_{in} - m_{out} + m_{rxn}$$

$$0 = QC_{in} - QC - VkC$$

Solve for C:

$$C = C_{in} \times \frac{Q}{Q + kV}$$
$$= C_{in} \times \frac{1}{1 + \left(k \times \frac{V}{Q}\right)}$$

Substituting the given values, the numerical solution is:

$$C = 100\ mg/L \times \frac{50\ m^3/day}{50\ m^3/day + (0.216/day)(500\ m^3)}$$
$$= 32\ mg/L$$

Example: 2

The manufacturing process that generates the waste in Example 1 has to be shut down, and starting at t = 0, the concentration C_{in} entering the CMBR is set to 0. What is the outlet concentration as a function of time after the concentration is set to 0? How long does it take the tank concentration to reach 10 percent of its initial, steady-state value?

Solution:

The tank is again the control volume. In this case, the problem is clearly non-steady state, because conditions change as a function of time. The mass balance equation is:

$$\frac{dm}{dt} = m_{in} - m_{out} + m_{rxn}$$

$$V\frac{dC}{dt} = 0 - QC - kCV$$

Solve for dC/dt :

$$\frac{dC}{dt} = -\left(\frac{Q}{V} + k\right)C$$

To determine C as a function of time, the preceding differential equation must be solved. Rearranged and integrate:

$$\int_{C_0}^{C_t} \frac{dC}{dt} = \int_0^t \left(\frac{Q}{V} + k\right) dt$$

Integration yields

$$ln\ C - ln\ C_0 = -\left(\frac{Q}{V} + k\right) t$$

$$ln\left(\frac{C}{C_0}\right) = -\left(\frac{Q}{V} + k\right)t$$

which yields

$$\frac{C_t}{C_0} = e^{-(Q/V+k)t}$$

We can verify that this solution is reasonable by considering what happens at $t = 0$ and $t = \infty$. At $t = 0$, the exponential term is equal to 1, and $C = C_0$, as expected. As $t \rightarrow \infty$, the exponential term approaches 0.

We can now plug in values to determine the dependence of *C* on time. Example 1 provides *Q* and *V*. The initial concentration is equal to the concentration before C_{in} was set to 0, which was found to be 32 mg/L in Example 1. Plugging in these values yields the outlet concentration as a function of time:

$$C_t = 32\,mg/L \times exp\left[-\left(\frac{50\ m^3/day}{500\ m^3} + \frac{0.216}{day}\right)t\right]$$

$$= 32\,mg/L \times exp\left(-\frac{0.316}{day}t\right)$$

How long will it take the concentration to reach 10 percent of its initial, steady-state value? That is, at what value of *t* is $C_t/C_0 = 0.10$? At the time when $C_t/C_0 = 0.10$,

Example: 3

The CMBR reactor depicted is filled with clean water prior to being started. After start-up, a waste stream containing 100 mg/L of a conservative pollutant is added to the reactor at a flow rate of 50 m^3/day. The volume of the reactor is 500 m^3. What is the concentration exiting the reactor as a function of time after it is started?

Again, the tank will serve as a control volume. We are told that the pollutant is conservative, so $m_{rxn} = 0$. The problem asks for concentration as a function of time, so the mass balance must be non-steady state.

The mass balance equation is

$$\frac{dm}{dt} = m_{in} - m_{out} + m_{rxn}$$

$$V\frac{dC}{dt} = QC_{in} - QC + 0$$

Solve for dC/dt:

Because of the extra term on the right (C_{in}), this question cannot be immediately solved. However, with a change of variables, we can transform the mass balance equation into a simpler form that can be integrated directly, using the same method as in Example 4.4. Let $y = (C - C_{in})$. Then $dy/dt = (dC/dt) - d(C_{in}/dt)$. Since C_{in} is constant, $dC_{in}/dt = 0$, so $dy/dt = dC/dt$. Therefore, the last of preceding equations is equivalent to

$$\frac{dy}{dt} = \frac{Q}{V} y$$

Rearranged and integrate:

$$\int_{y(0)}^{y(t)} \frac{dy}{y} = \int_0^t -\frac{Q}{V} dt$$

Integration yields: $ln\left(\frac{y(t)}{y(0)}\right) = -\frac{Q}{V}t$

or $\frac{y(t)}{y(0)} = e^{-(Q/V)t}$

Replacing y with $(C - C_{in})$ results in the following equation:

$$\frac{C - C_{in}}{C_0 - C_{in}} = e^{-(Q/V)t}$$

Since clean water is present in the tank at start-up, $C_0 = 0$:

$$\frac{C - C_{in}}{\quad} = e^{-(Q/V)t}$$

Rearranged to solve for *C*:

$$C - C_{in} = -C_{in}e^{-(Q/V)t}$$

$$C = C_{in} \times \left(1 - e^{-(Q/V)t}\right)$$

This is the solution to the question posed in the problem statement:

Note what happens as $t \rightarrow \infty$: $e^{-(Q/V)t} \rightarrow 0$, and $C \rightarrow C_{in}$.

This is not surprising, since the substance is conservative. If the reactor is run long enough, the concentration in the reactor will eventually reach the inlet concentration.

Reactor design

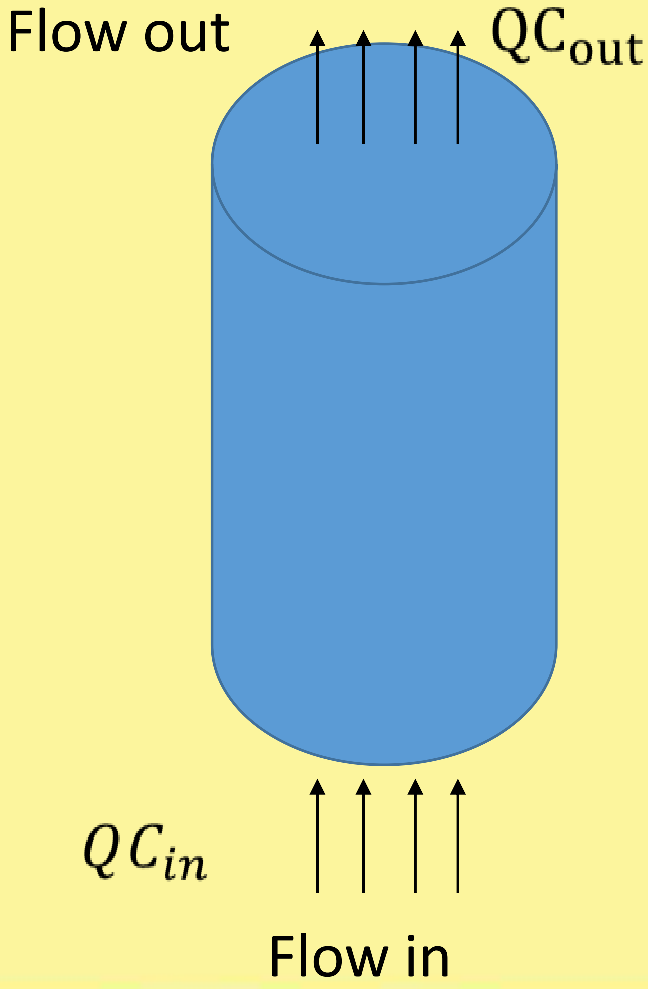
Mode of operation

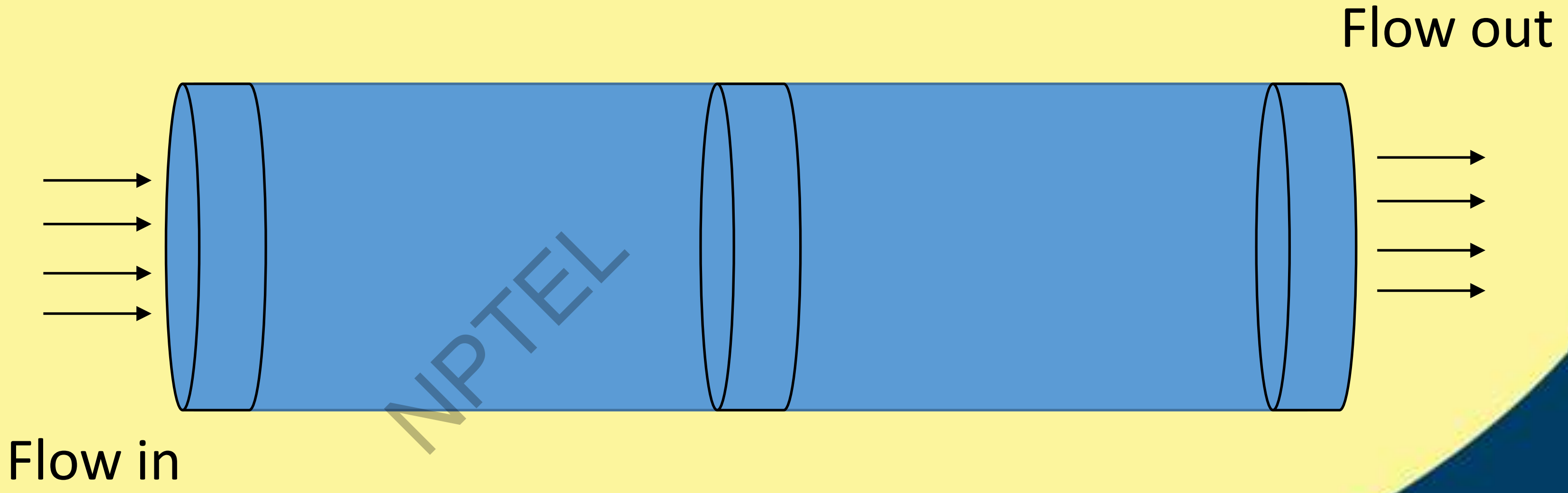
1. ~~Batch reactor/ Completely mixed batch reactor (CMBR)~~
2. ~~Continuous reactor/continuous stirred tank reactor (CSTR)~~
3. Plug flow reactor

Reactor kinetics

1. Reaction order zero
2. First order reaction
3. Second order reaction

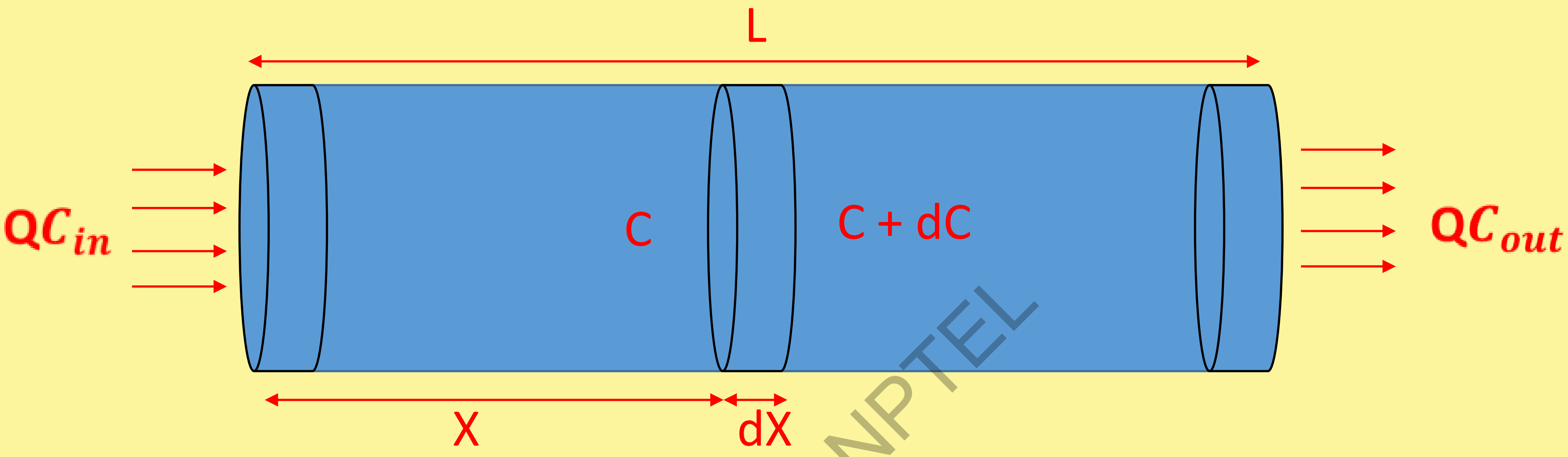
Plug Flow Reactor (PFR)





Length >> Width

Plug flow reactor (PFR)

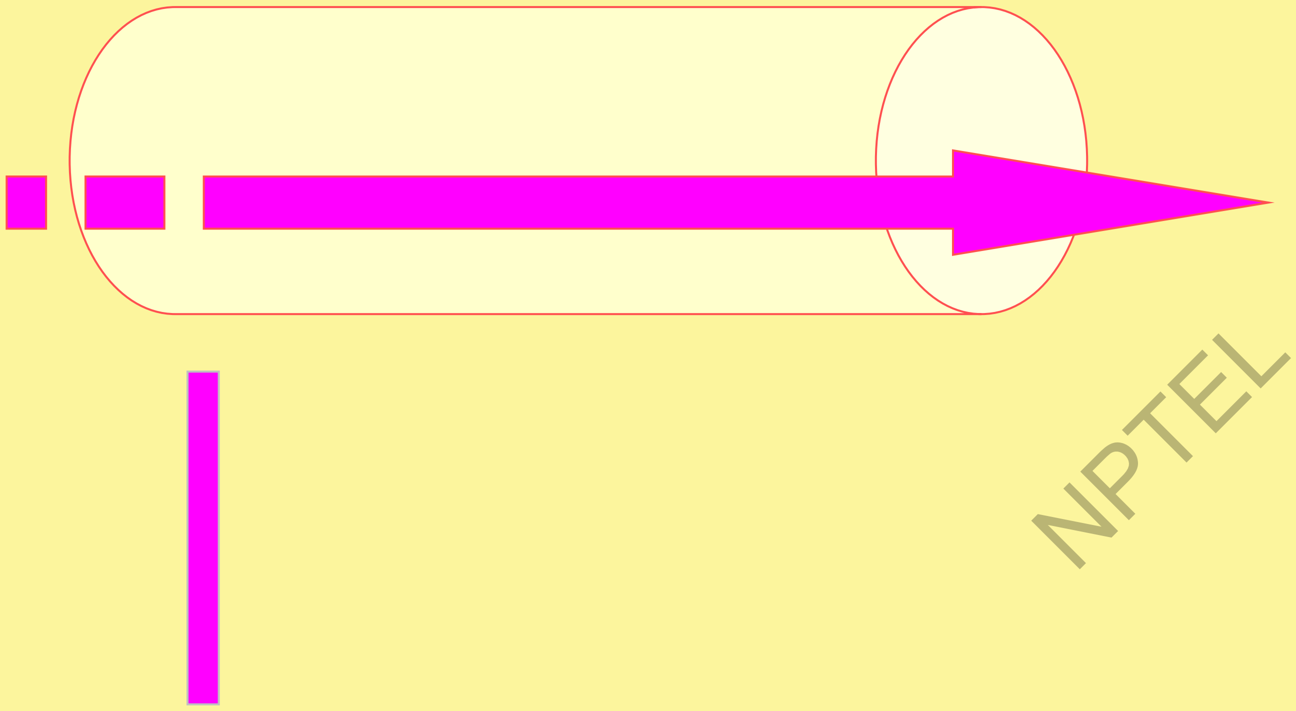


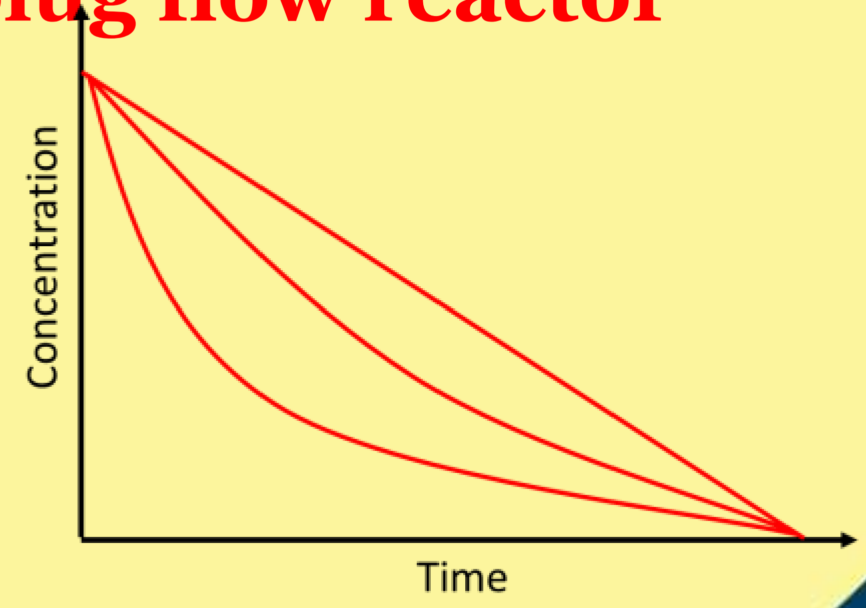
V – Reactor volume

A – cross-sectional area

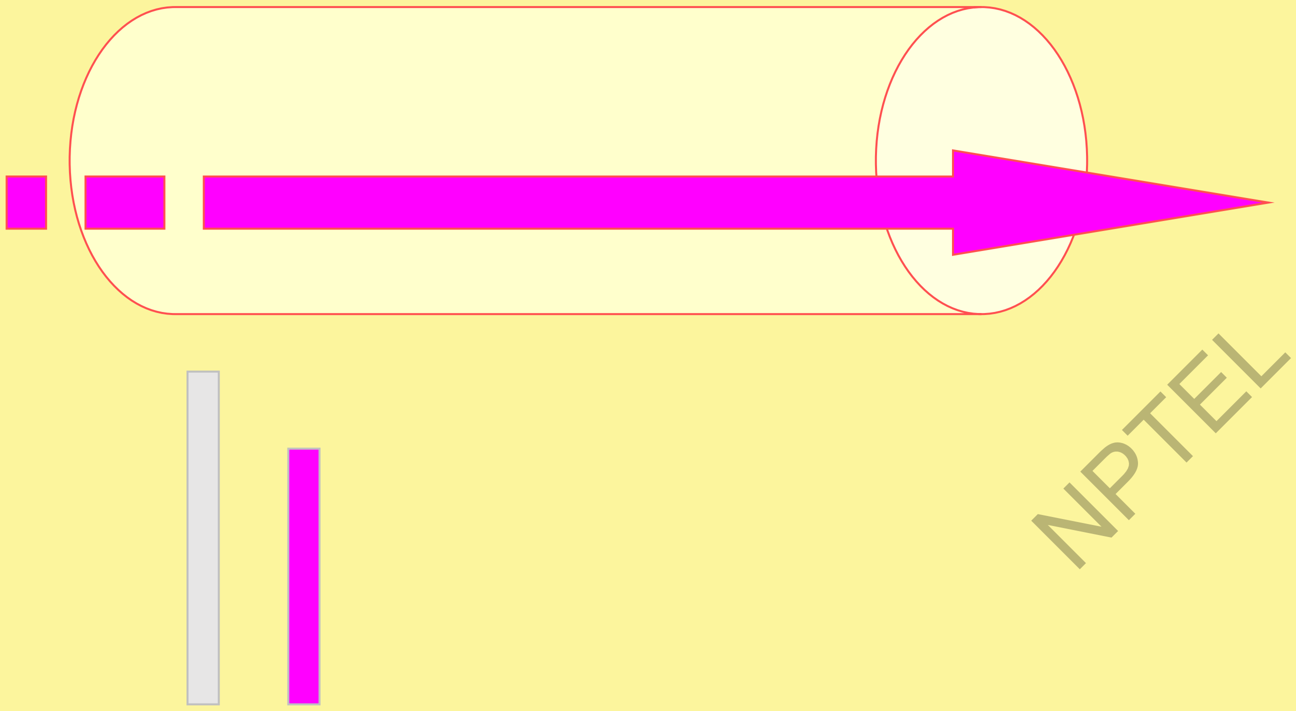
dx - elemental length, volume of elemental length = dv = A. dx

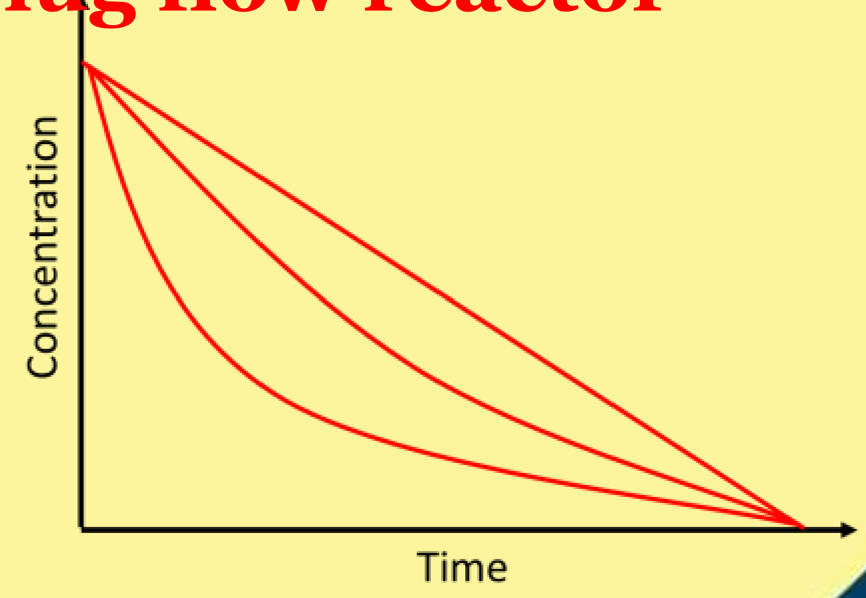
Variation of pollutant removal in plug flow reactor





Variation of pollutant removal in plug flow reactor





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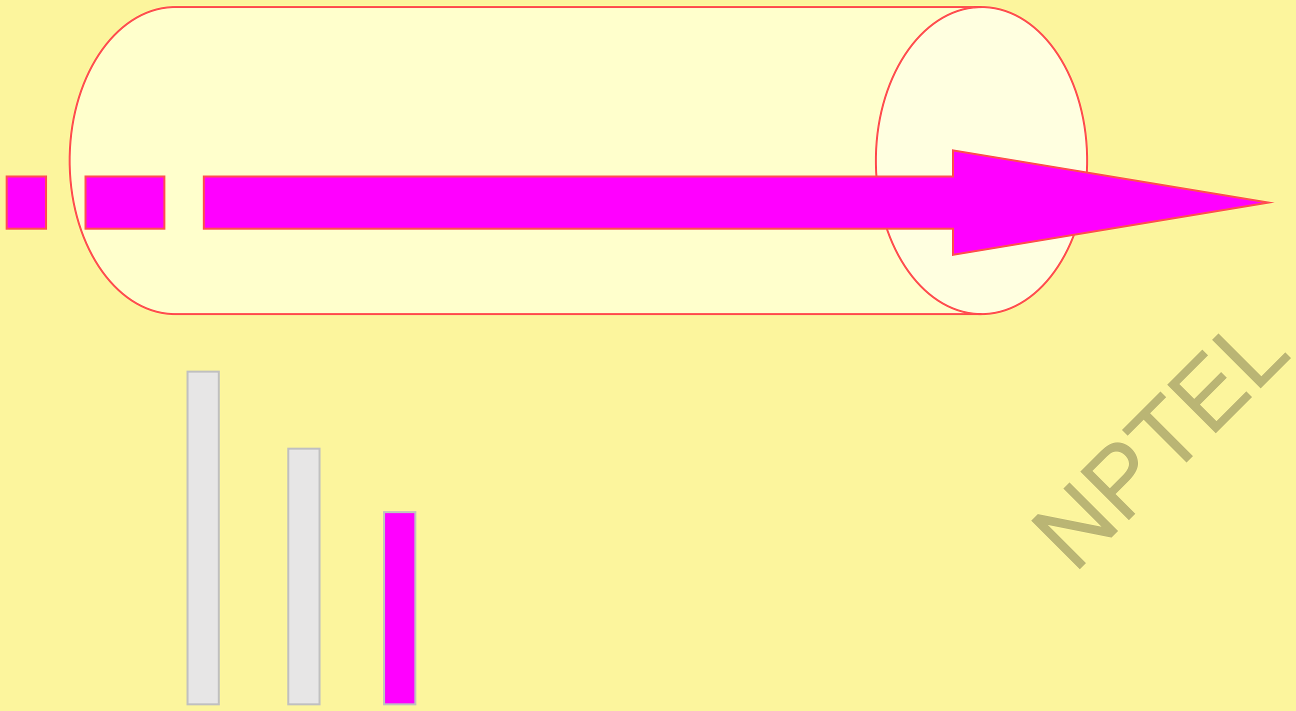
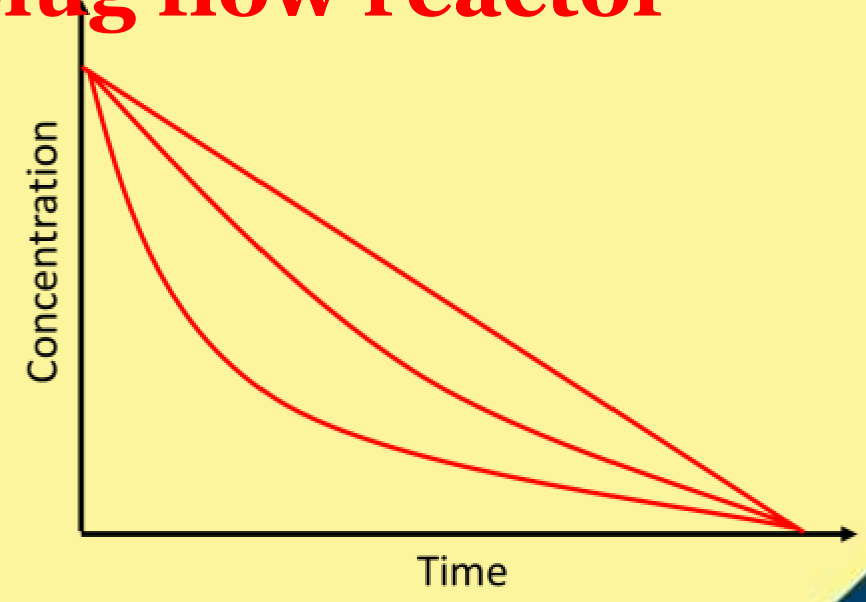
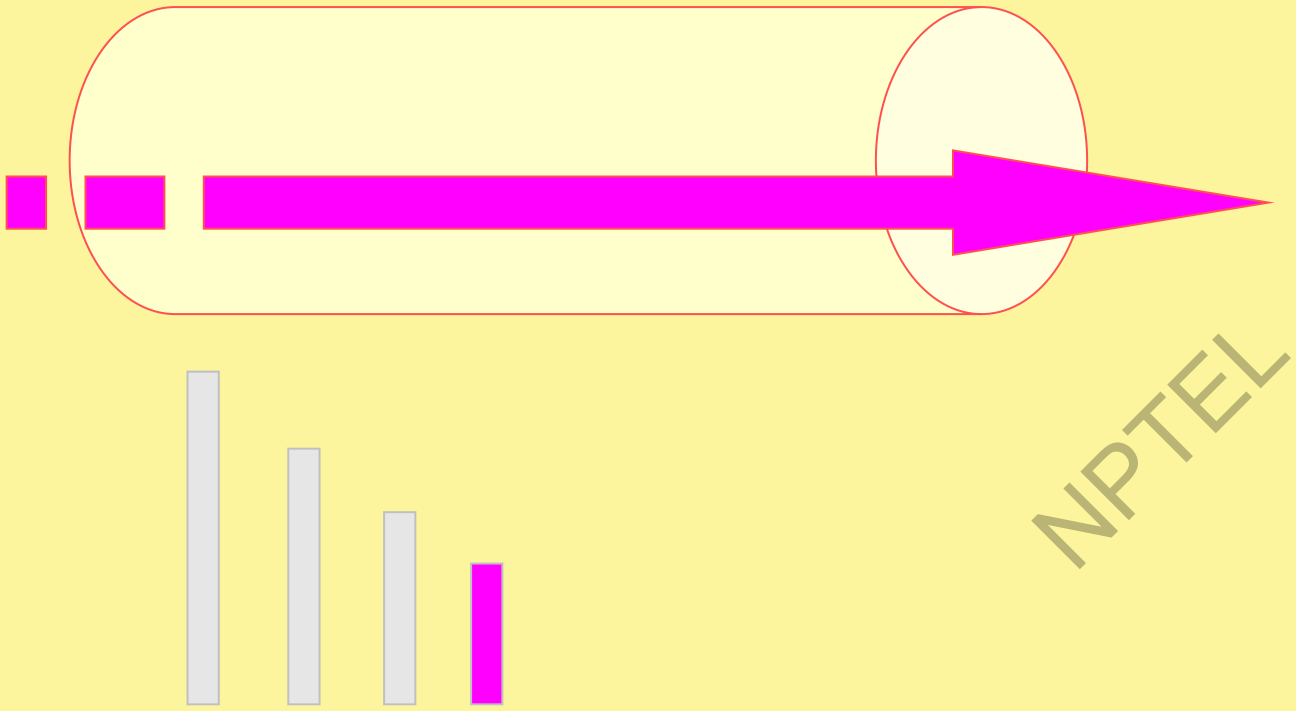
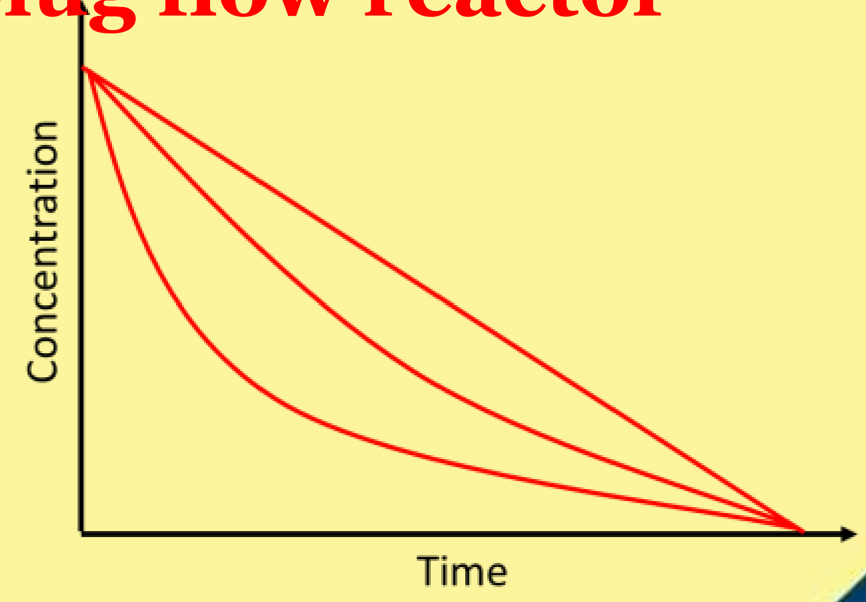




Variation of pollutant removal in plug flow reactor





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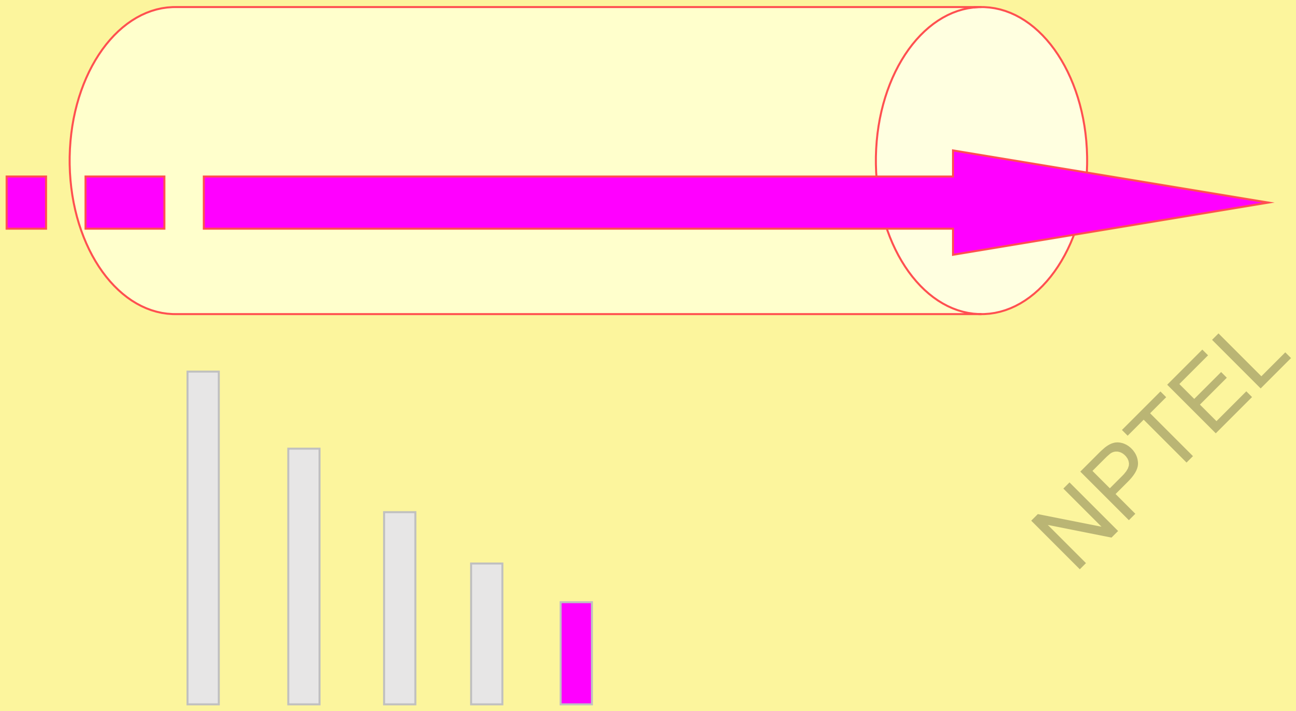
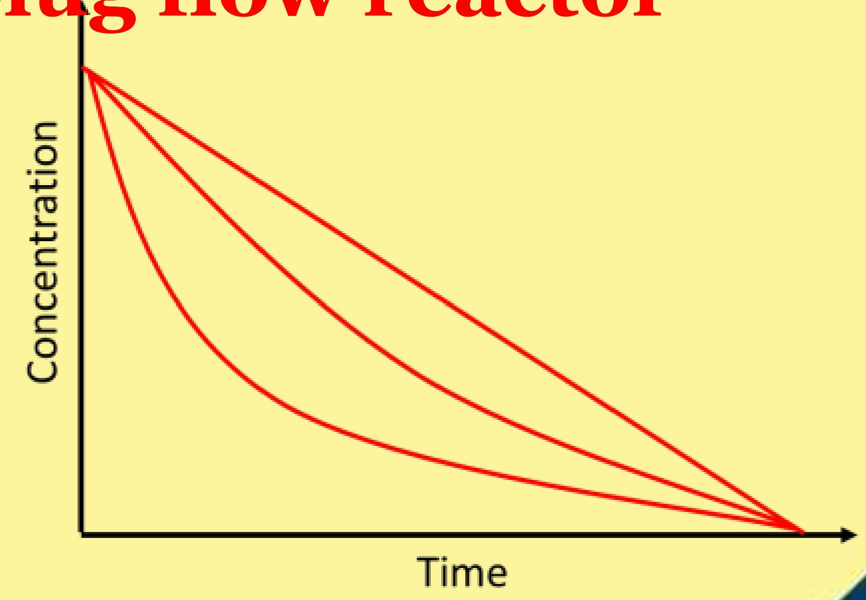
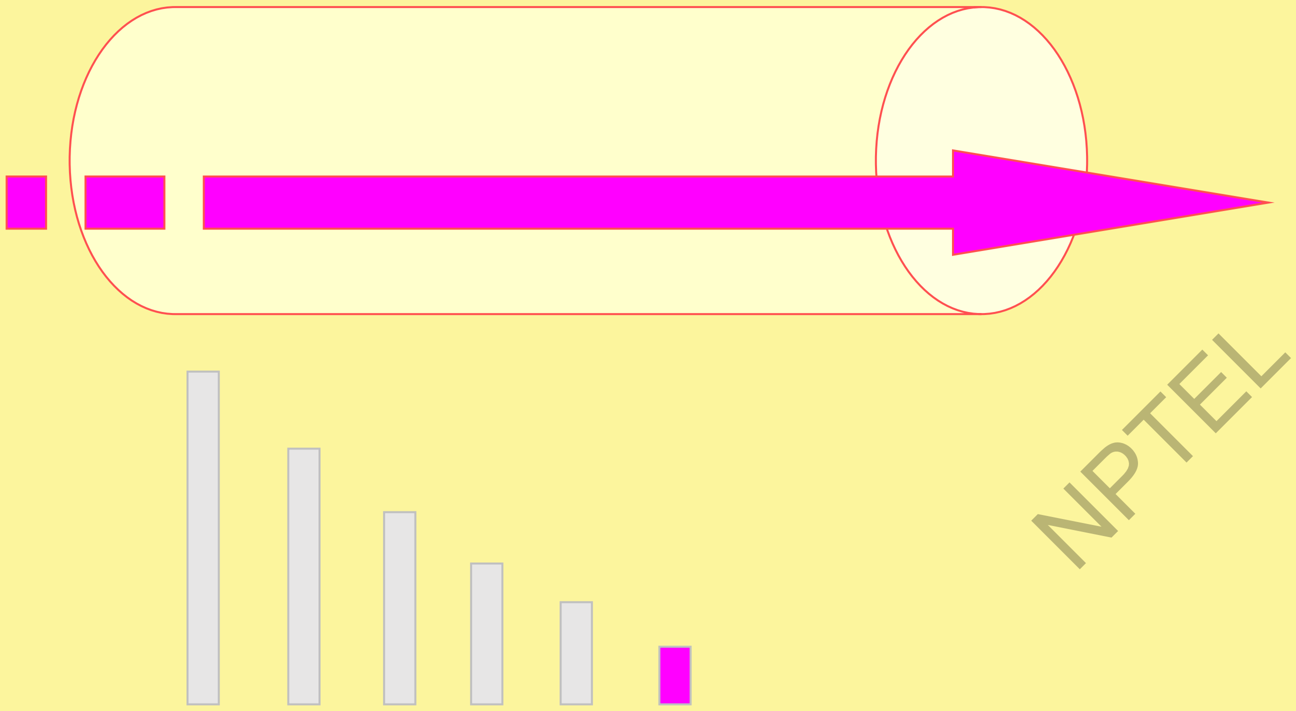
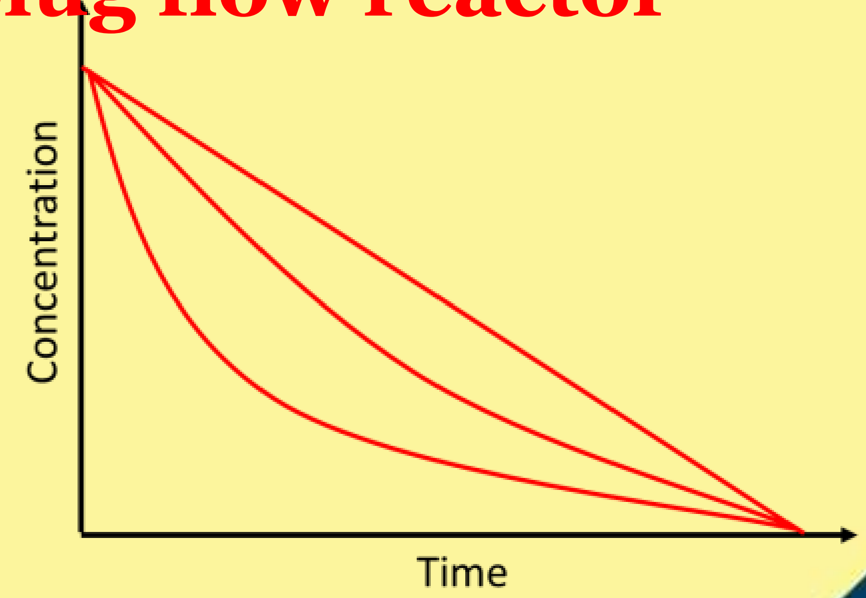


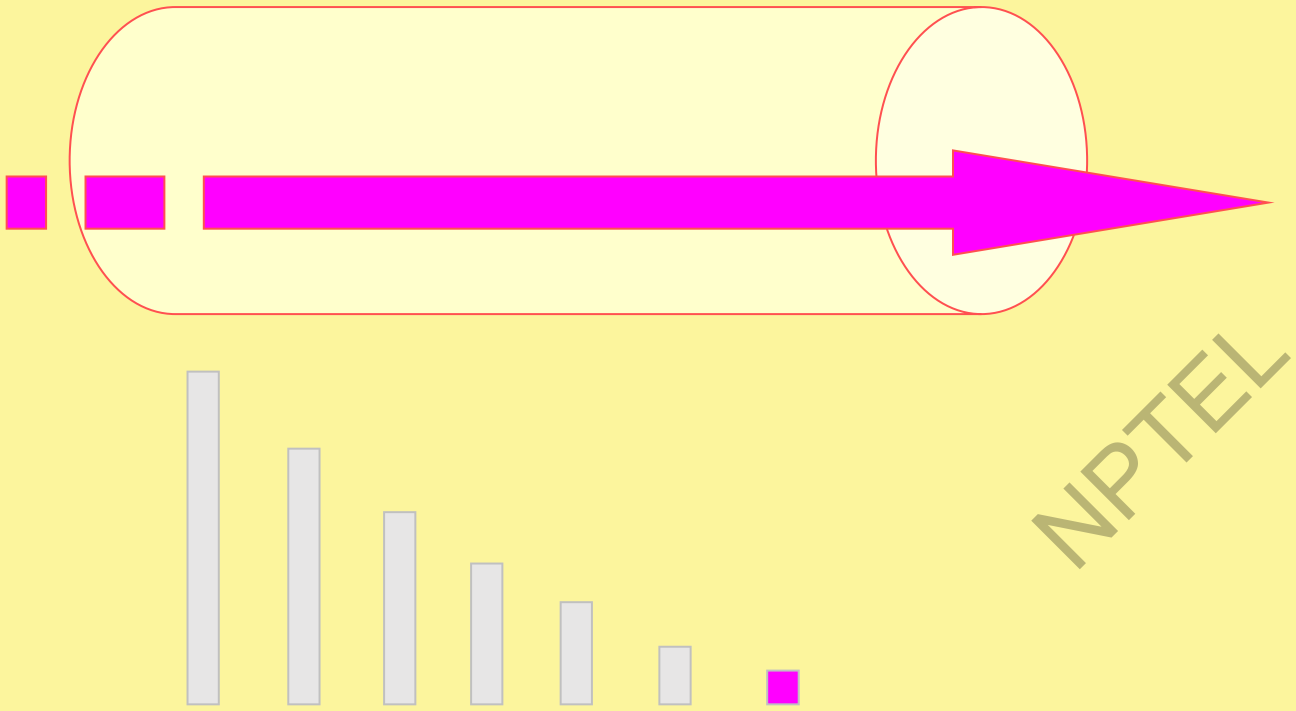


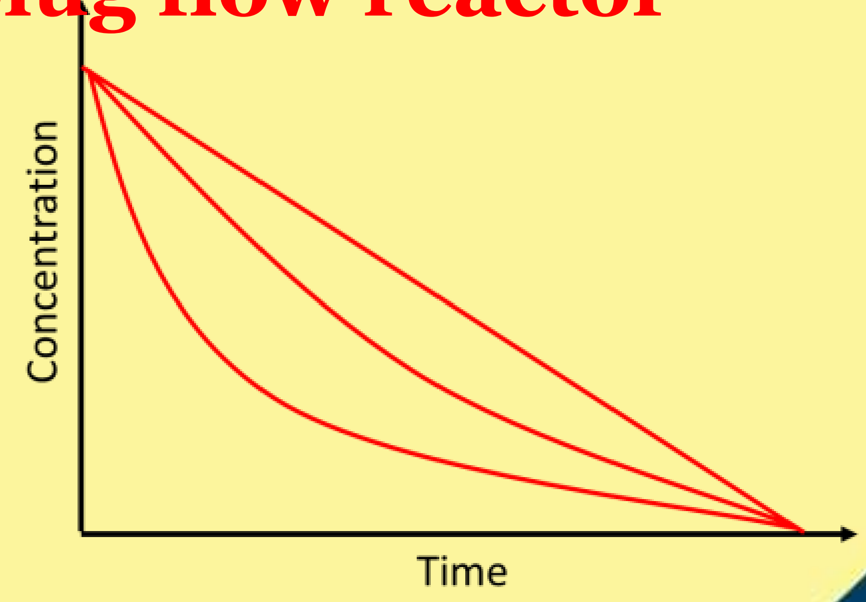
Variation of pollutant removal in plug flow reactor



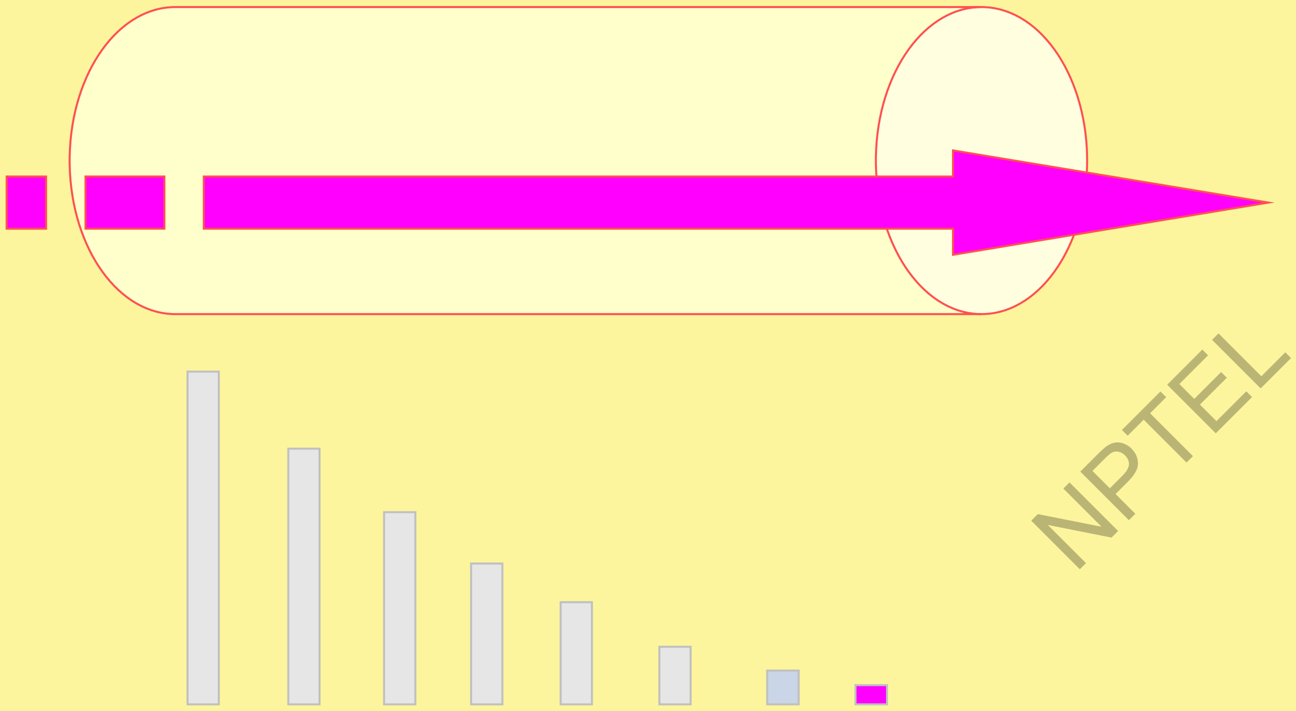


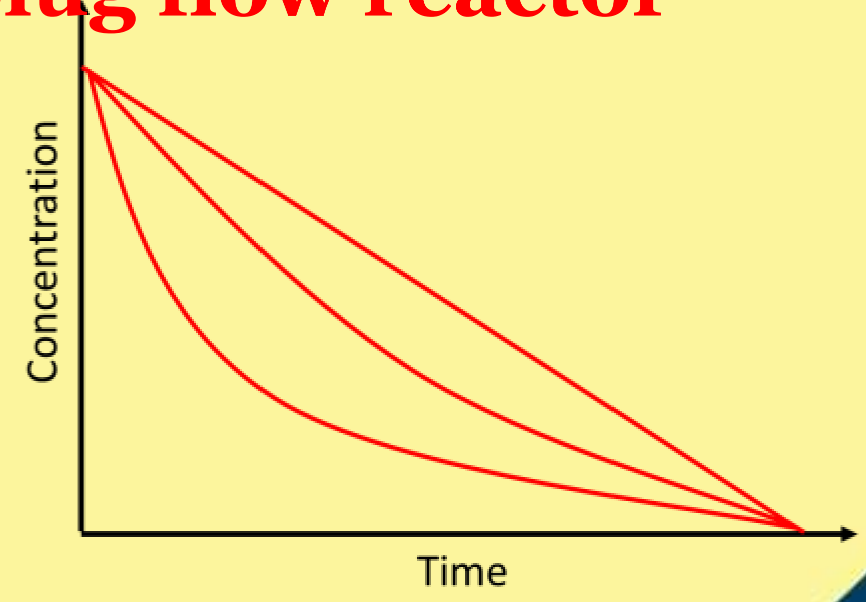
Variation of pollutant removal in plug flow reactor





Variation of pollutant removal in plug flow reactor





Plug flow reactor (PFR)

Mass balance for element c in elementary section

$$0 = \acute{m}_{in} - \acute{m}_{out} + (\frac{dm}{dt})_{reaction}\, dV$$

$$\acute{m}_{in} = QC_0$$

$$\acute{m}_{in} = Q(C + dC)$$

$$0 = QC_0 - Q(C_0 + dC) - (\frac{dm}{dt})_{reaction}\, dV$$

Plug flow reactor (PFR): First order reaction

$$0 = QC_0 - Q(C_0 + dC) - (\frac{dm}{dt})_{reaction}\, dV$$

For first order reaction $\frac{dm}{dt}$ = kc

$$C_0 - (C + dC) - kC\, dV/Q = 0$$

$$\{C_0 - (C_0 + dC)\}/C = k\, dV/Q$$

$$dC/C = -k\, dx.\, A/Q$$

$$\int_{C_0}^{C_e} \frac{dC}{C} = \int_0^L -\frac{kA}{Q}\, dx$$

$$[ln]_{C_0}^{C_e} = -\frac{kA}{Q}[x]_0^L$$

$$Ln(c_e/c_o) = -\frac{kAL}{Q} = -k\Theta$$

$$c_e = c_o e^{-k\Theta}$$

Reaction HRT

$\theta = V/Q$

Example: 4

Calculate the retention times in the CMBR operate at a flow rate of 50 m^3/day. The volume of the reactor is 500 m^3.

Solution:

For the CMBR,

$$\theta = \frac{V}{Q} = \frac{500\ m^3}{50\ m^3/day} = 10\ days$$

Example: 5

Determine the volume required for a PFR to obtain the same degree of pollutant reduction as the CMBR in Example 1. Assume that the flow rate and first-order decay rate constant are unchanged ($Q = 50\ m^3/day\ and\ k = 0.216/day$)

The CMBR in Example 1 achieved a pollutant decrease of $C_{out}/C_{in} = 32/100 = 0.32$. F plug flow reactor,

$$\frac{C_{out}}{C_{in}} = e^{-(kV/Q)}$$

Or

$$0.32 = exp - \left(\frac{0.126/day \times V}{50\, m^3/day}\right)$$

Solve for *V*:

$$V = ln\, 0.32 \times \frac{50\, m^3/day}{-0.216/day}$$

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Thank you

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Course Name: Introduction to Environmental Engineering and Science – Fundamentals and Sustainability Concepts

Faculty Name: Dr. Brajesh Kumar Dubey

Department : Civil engineering

Topic Physical Process in Environment

Lecture 18: Energy Balance

Energy Balances

Why is it necessary to do energy balance?

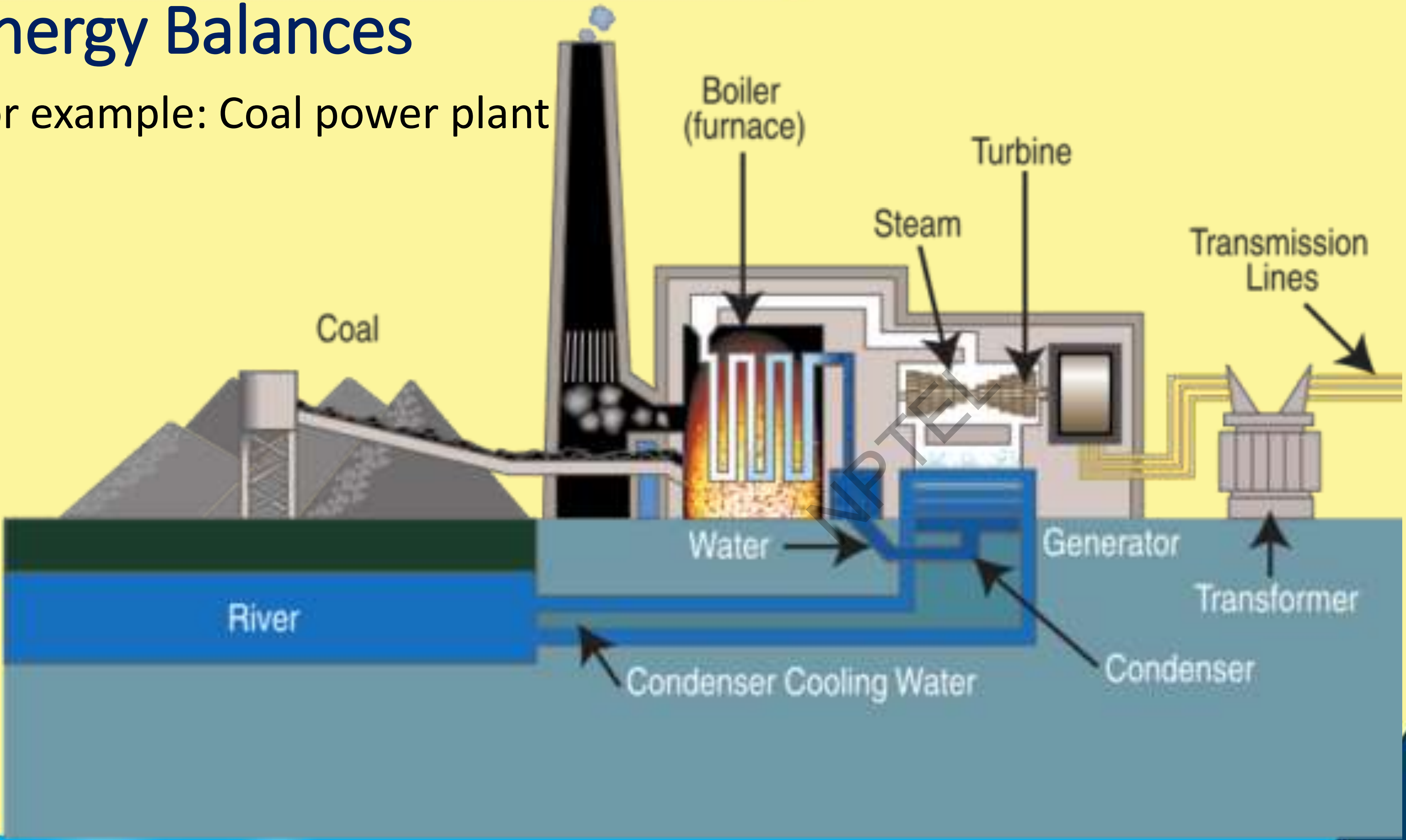
The first law of thermodynamics is a version of the law of conservation of energy, adapted for thermodynamic systems. The law of conservation of energy states that the total energy of an isolated system is constant; energy can be transformed from one form to another, but can be neither created nor destroyed. The first law is formulated as

$$\Delta U = Q - W$$

It states that the change in the internal energy ΔU of a closed system is equal to the amount of heat Q supplied to the system, minus the amount of work W done by the system on its surroundings

Energy Balances

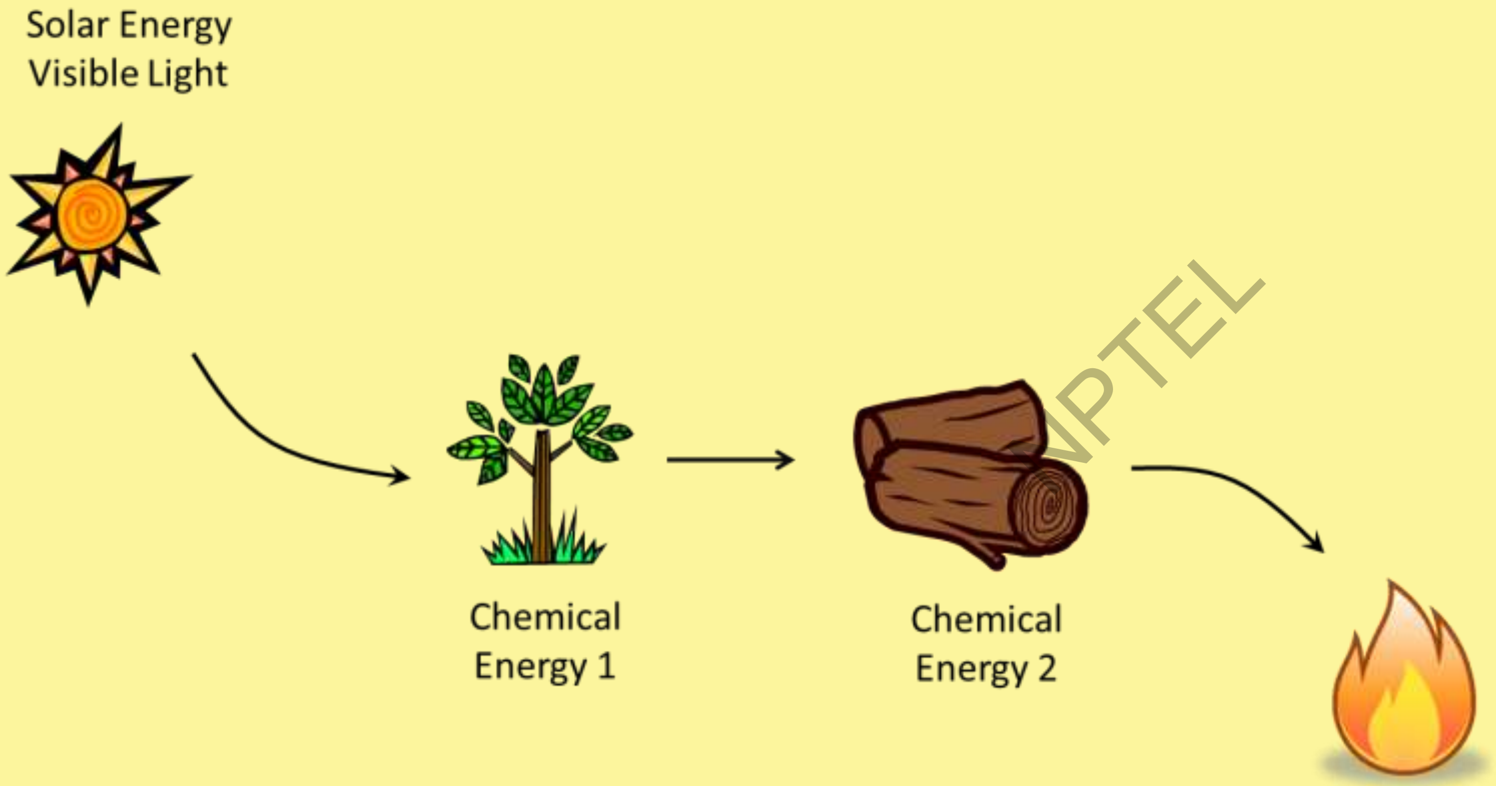
For example: Coal power plant



Source: https://newlook.dteenergy.com

Energy Balances

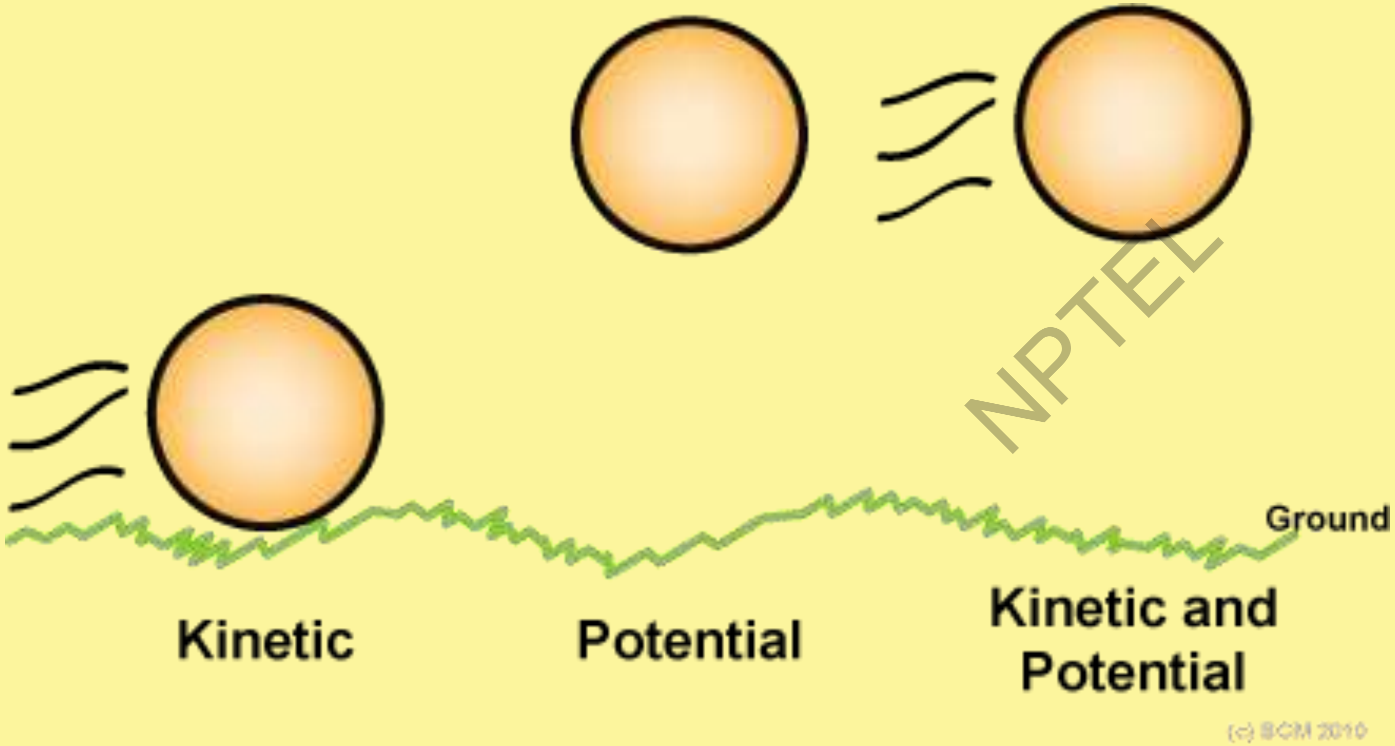
Common forms of energy: Heat and chemical energy



Source: http://breaking-dawn.tk.com

Energy Balances

Common forms of energy: Kinetic and potential energy



Source: http://breaking-dawn.tk.com

Energy Balances

Common forms of energy: Electromagnetic energy

Energy Balances

Common forms of energy: calculation formula

Energy	Formula
Heat internal energy	ΔE = mass × Heat capacity (c) × ΔT
Chemical internal energy	ΔE = $\Delta H_{reaction}$ at constant time
Gravitational energy	ΔE = mass × Δ height
Kinetic energy	E = mass × velocity^2/2
Electromagnetic energy	E = Planck's constant × photon frequency

Energy Balances

Conducting energy balance

(change in internal energy plus external energy per unit time)
= (energy flux in) – (energy flus out)

$$\frac{dE}{dt} = E_{in} - E_{out}$$

Example: 6

A 40-gallon electric water heater heats water entering the house, which has a temperature of 10 °C as it enters the heater. The heating level is set to the maximum while several people take consecutive showers. If, at the maximum heating level, the heater uses 5 kW of electricity and the water use rate is a continuous 2 gallons/min, what is the temperature of the water exiting the heater? Assume that the system is at steady state and the heater is 100 percent efficient; that is, it is perfectly insulated, and all of the energy used heats the water.

The control volume is the water heater. Because the system is at steady state, dE/dt is equal to zero. The energy flux added by the electric heater heats water entering the water heater to the temperature at the outlet. The energy balance is thus

$$\frac{dE}{dt} = 0 = E_{in} - E_{out}$$

The energy flux into the water heater comes from two sources: the heat content of the water entering the heater and the electrical heating element. The heat content of the water entering the heater is the product of the water-mass flux, the heat capacity, and the inlet temperature. The energy added by the heater is given as 5 kW.

The energy flux out of the water heater comes from two sources: the heat content of the water entering the heater and the electrical heating element. The heat content of the water entering the heater is the product of the water-mass flux, the heat capacity, and the inlet temperature. The energy added by the heater is given as 5 kW.

The energy flux out of the water heater is just the internal energy of the water leaving the system $(m_{H_2O} \times c \times T_{out})$. There is no net conversion of other forms of energy. Therefore, the energy balance may be rewritten as follows:

$$0 = \left(m_{H_2O}cT_{in} + 5kW\right) - m_{H_2O}cT_{out}$$

Each term of this equation is an energy flux and has the units of energy/time. To solve, place each term in the same units–in this case, watts (1 W equals 1 J/s, and 1,000 W = 1 kW). In addition, the water flow rate (gallons/min) needs to be converted to units of mass of water per unit time using the density of water. Combining the first and third terms,

$$0 = m_{H_2O}c(T_{out} - T_{in}) + 5kW$$

$$0 = \frac{2\text{ gal H}_2\text{O}}{\text{min}} \times \frac{3.785\text{ L}}{\text{gal}} \times \frac{1.0\text{ kg}}{\text{L}} \times \frac{4{,}184\text{ J}}{\text{kg} \times {}^\circ\text{C}} \times (T_{in} - T_{out}) + \frac{5{,}000\text{ J}}{\text{s}} \times \frac{60\text{ s}}{\text{min}}$$

$$= 3.16 \times 10^4 \frac{\text{J}}{\text{min} \times {}^\circ\text{C}} \times (\text{T}_{\text{in}} - \text{T}_{\text{out}}) + 3.00 \times 10^5 \frac{\text{J}}{\text{min}}$$

Solve for T_{out}

$$\text{T}_{\text{out}} = \text{T}_{\text{in}} + 9.5^\circ\text{C} = (10 + 9.5) = 19.5^\circ\text{C}$$

This is a cold shower! But it makes sense; many people have taken such a cold shower after the hot water in the tank was used up by previous showers.

Example: 7

Example 6 showed that it is necessary to wait until the water in the tank is reheated (hopefully, by passive solar energy!) before taking a hot shower. How long would it take the temperature to reach 54 °C if no hot water were used during the heating period and the water temperature entered the heater at 20 °C?

Solution:

In this case, assuming the homeowner is not taking advantage of solar energy, the only energy input is the electrical heat, and no energy is leaving the tank. Therefore, the rate of increase in internal energy is equal to the rate at which electrical energy is used:

$$\frac{dE}{dt} = E_{in} - E_{out} = E_{in} - 0$$

From Table, $\Delta E = mass \times c \times \Delta T$, so we can express the relationship as follows:

$$\frac{dE}{dt} = \frac{(mass\ of\ H_2O) \times c \times \Delta T}{\Delta t}$$

and $\frac{(mass\ of\ H_2O)\times c\times \Delta T}{} = E_{in} = 5{,}000\ J/s$

This expression can be solved for the change in time, Δt, given that ΔT is equal to $54°C - 20°C = 34°C$:

$$\Delta t = \frac{(mass\ of\ H_2O) \times c \times \Delta T}{5{,}000\, J/s}$$

$$= \frac{\left(40\ gal\ H_2O \times \frac{3.785\ L}{gal} \times \frac{1.0\ kg}{L}\right)\left(4{,}184\frac{L}{kg \times °C}\right)(54°C - 20°C)}{5{,}000\, J/s}$$

$$= 4.3 \times 10^3 s = 1.2\ h$$

Example: 8

The second law of thermodynamics states that the heat energy cannot be converted to work with 100 percent efficiency. As a result, a significant fraction of the heat released in electrical power plants is lost as waste heat; in modern large power plants, this loss accounts for 65-70 percent of the total heat released from combustion.

A typical coal-fired electrical power plant produces 1,000 MW of electricity by burning fuel with an energy content of 2,800 MW; 340 MW are lost as heat up the smokestack, leaving 2,460 MW to power turbines that drive a generator to produce electricity.

Example: 8

However, the thermal efficiency of the turbines is only 42 percent. That means 42 percent of this power goes to drive the generator, but the rest (58 percent of 2,460 = 1,430 MW) is waste heat that must be removed by cooling water. Assume that cooling water from an adjacent river, which has a total flow rate of 100 m³és, is used to remove the waste heat. How much will the temperature of the river rise as a result of the addition of this heat?

This problem is similar to Example 6, because a specified amount of heat is added to a flow of water, and the resulting temperature rise must be determined. An energy balance can be written over the region of the river to which the heat is added. Here, T_{in} represents the temperature of the water upstream, and T_{out} represents the temperature after heating:

$$\frac{dE}{dt} = E_{in} - E_{out}$$

$$0 = (1{,}430\ MW\ of\ heat\ from\ power\ plant)$$
$$+(m_{H_2O} \times c \times T_{H_2O_{in}})$$
$$-(m_{H_2O} \times c \times T_{H_2O_{out}})$$

Rearranging,

$$m_{H_2O} \times c \times (T_{out} - T_{in}) = 1{,}430\ MW$$

The remainder of this problem is essentially unit conversion. To obtain m_{H_2O} requires multiplication of the given river volumetric flow rate by the density of water (approximately 1,000 kg/m^3). The heat capacity of water, $c =$ 4,184 J/kg°C , also is required. Thus,

$$\left(100\,\frac{m^3}{s} \times 1{,}000\,\frac{kg}{m^3}\right) \times \left(4{,}184\,\frac{J}{kg \times {}^\circ\mathrm{C}}\right) \times \Delta T = 1{,}430 \times 10^6\, J/s$$

Solving for ΔT:

$$\Delta T = 3.4^\circ\mathrm{C}$$

Consideration of this temperature increases is important, as the Henry's law constant for oxygen changes with temperature. This results in a reduced dissolved-oxygen concentration in the river in warmer water, which may be harmful to aquatic life.

NPTEL ONLINE CERTIFICATION COURSES

Thank you

NPTEL ONLINE CERTIFICATION COURSES

Course Name: Introduction to Environmental Engineering and Science – Fundamentals and Sustainability Concepts

Faculty Name: Dr. Brajesh Kumar Dubey

Department : Civil engineering

Topic Physical Process in Environment

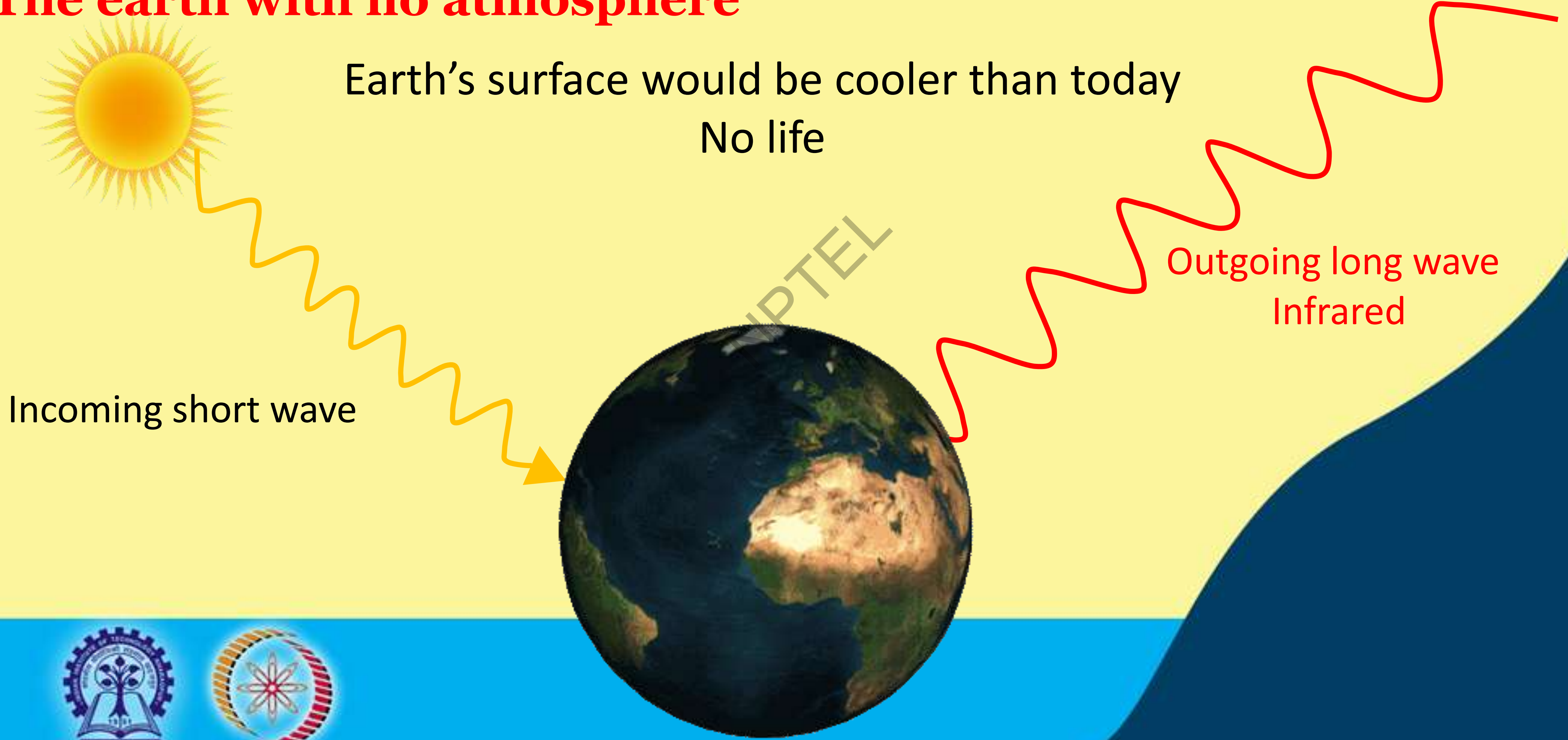
Lecture 19: Energy Balance, Earth Overshot Days

Energy balance of Earth

The earth with no atmosphere

Earth’s surface would be cooler than today

No life



The earth has an atmosphere!!

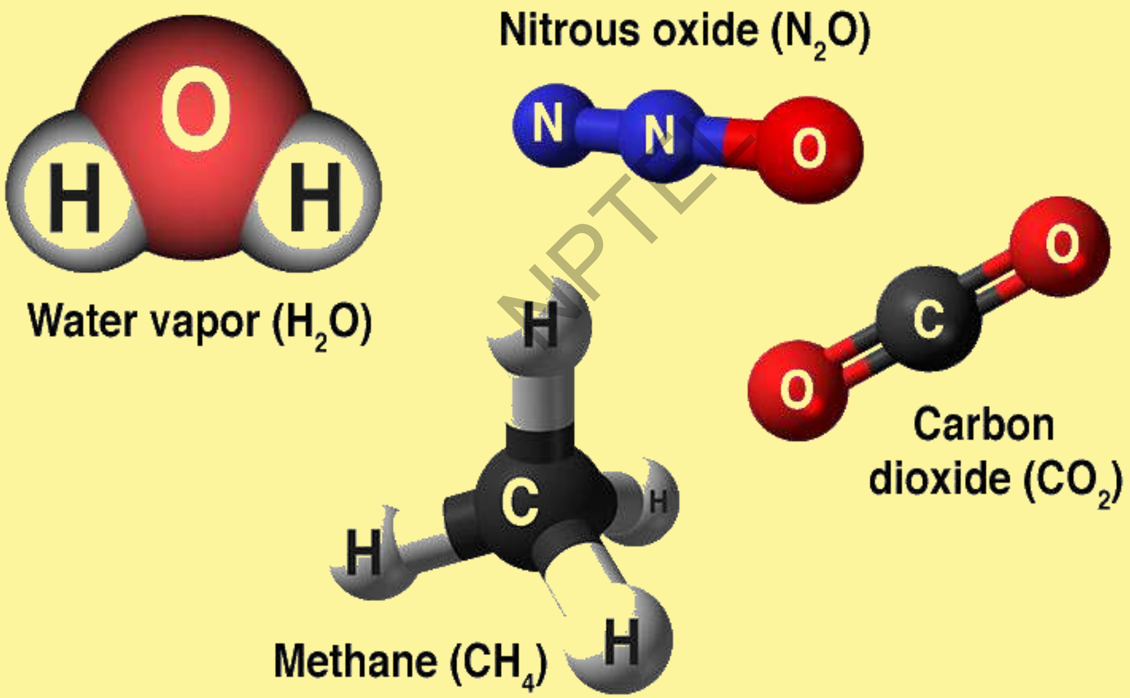
Includes gases such as nitrogen and oxygen
Also includes greenhouse gases.

Source: https://climate.nasa.gov.com

What is a Greenhouse Gas?

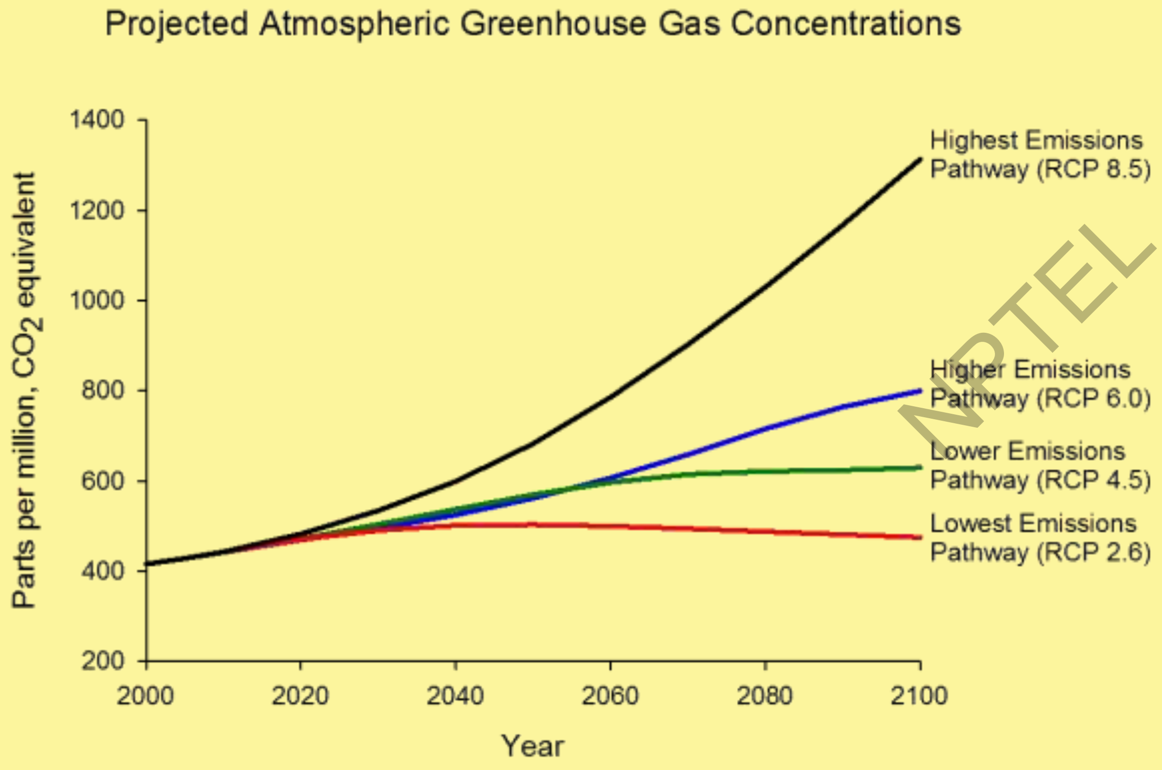
A greenhouse gas is a gas that absorbs and emits radiant energy within the thermal infrared range. Greenhouse gases cause the greenhouse effect.

- Some examples:
  - Water vapor
  - Carbon dioxide
  - Nitrous oxide
  - Methane



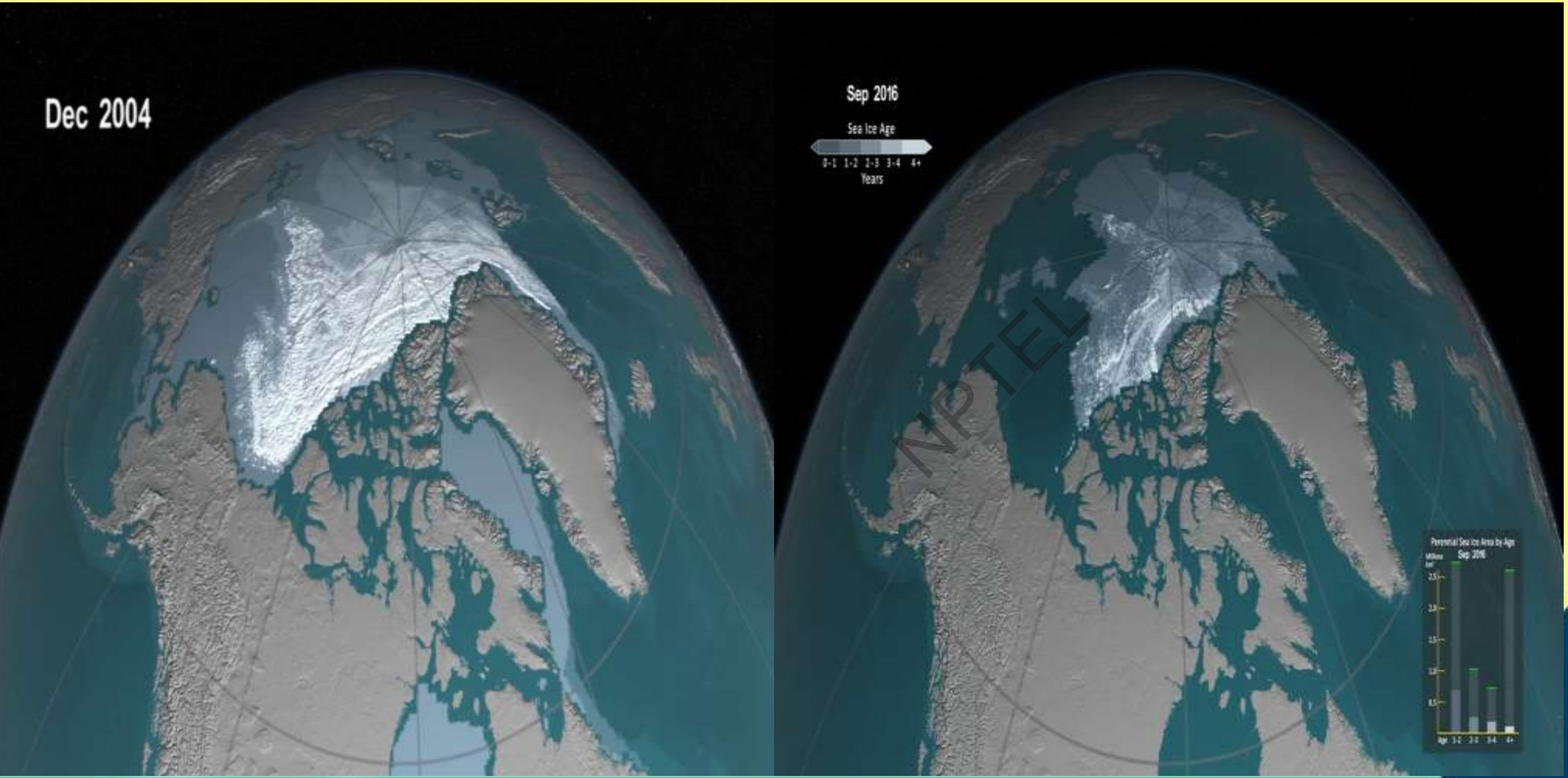
What is a Greenhouse Gas?

Greenhouse gases warm the earth in a similar way that blankets warm us at night



Source: US EPA

Causes of Greenhouse Gas: Global warming



Source: NASA

Earth Overshoot Day

As of July 29, humanity has officially used up more ecological resources this year than the Earth can regenerate by the end of the year. The occasion even has a name: Earth Overshoot Day.

The date has moved up two months over the past 20 years, and July 29 marks the earliest the date has ever landed.

'Earth's resource budget for 2019 spent by July 29'

Report says as of yesterday, humans used up the year's water, soil, clean air

#PARIS

Mankind will have used up its allowance of natural resources such as water, soil and clean air for all of 2019 by Monday, a report said. The so-called Earth Overshoot Day has moved up by two months over the past 20 years and this year's date is the earliest ever, the study by the Global Footprint Network said.

The equivalent of 1.75 planets would be required to produce enough to meet humanity's needs at current consumption rates.

"Earth Overshoot Day falling on July 29 means that humanity is currently using nature 1.75 times faster than our planet's ecosystems can regenerate. This is akin to using 1.75 earths," the environmental group, which is headquartered in Oakland, California, said in a statement.

"The costs of this global ecological overspending are becoming increasingly evident in the form of deforestation, soil erosion, biodiversity loss, or the buildup of carbon dioxide in the atmosphere.

The latter leads to climate change and more frequent extreme weather events," it added.

Calculated since 1986, the grim milestone has arrived earlier each year. In 1993, it fell on October 21, in 2003 on September 22, and in 2017 on August 2.

"We have only got one Earth -- this is the ultimately defining context for human existence. We can't use 1.75 (earths) without destructive consequences," said Mathis Wackernagel, founder of Global Footprint Network.

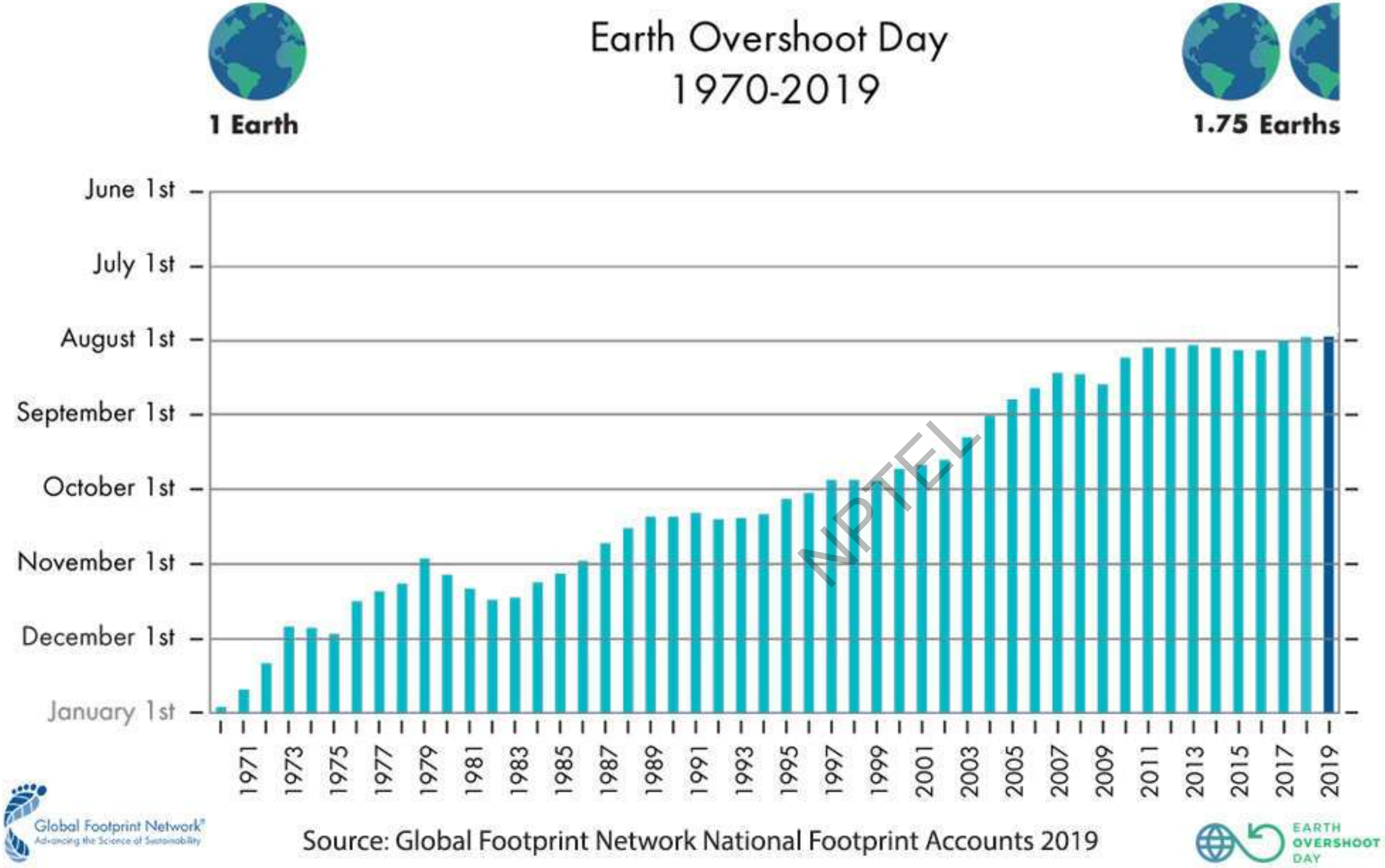
Maria Carolina Schmidt Zaldivar, Chile's environment minister and chair of the Climate COP25 scheduled this December in Santiago, said a major cause of the date falling earlier and earlier was growing amounts of CO_2 emissions.

"The importance of decisive action is becoming ever more evident," she said.

AFP

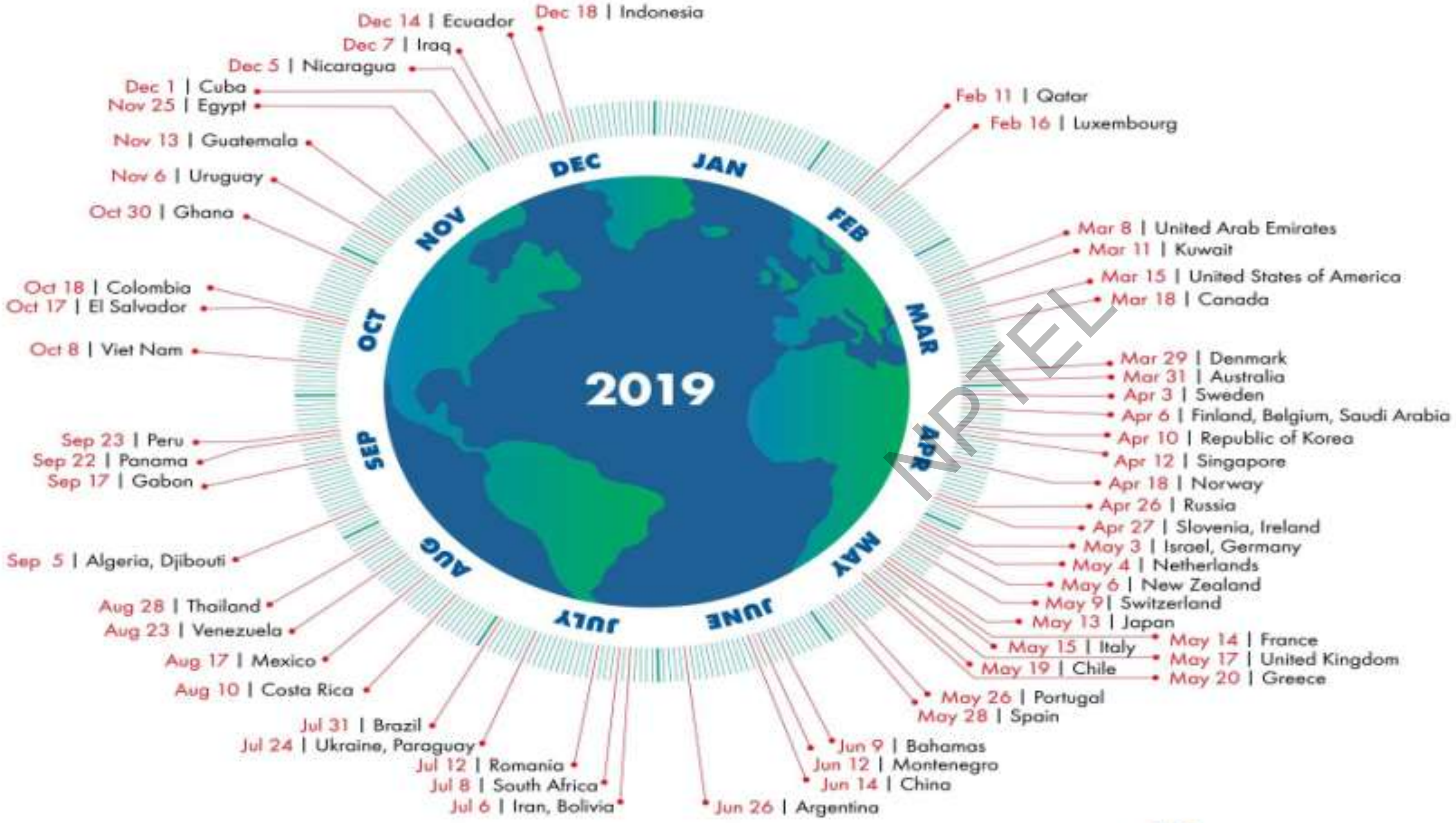
40,000 litres of diesel oil spill into sea in Chile

» **Chile's navy** has confirmed the spillage of 40,000 litres of diesel oil into the sea in a remote, pristine area of Patagonia. A navy statement said it received a call from the mining company CAP on Saturday reporting the spill at the terminal of Guarello island, so far one of the planet's most untouched, with important biodiversity.


Earth Overshoot Day
1970-2019
1 Earth
1.75 Earths
June 1st
July 1st
August 1st
September 1st
October 1st
November 1st
December 1st
January 1st
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Global Footprint Network
Source: Global Footprint Network National Footprint Accounts 2019
EARTH OVERSHOOT DAY

Country Overshoot Days 2019

When would Earth Overshoot Day land if the world's population lived like...



EARTH OVERSHOOT DAY

Source: Global Footprint Network National Footprint Accounts 2019

Global Footprint Network
Advancing the Science of Sustainability


How many countries are required
to meet the demand of its citizens…
Japan 7.7
Italy 4.7
Switzerland 4.6
U.K. 4.0
China 3.8
Portugal 3.2
Germany 3.0
Spain 2.9
India 2.7
U.S.A. 2.2
France 1.9
World 1.75
Source: Global Footprint Network National Footprint Accounts 2019
Global Footprint Network®
Advancing the Science of Sustainability
EARTH
OVERSHOOT
DAY

How many Earths do we need
if the world's population lived like…

U.S.A.	5.0
Australia	4.1
Russia	3.2
Germany	3.0
Switzerland	2.8
Japan	2.8
U.K.	2.7
France	2.7
Italy	2.7
Portugal	2.5
Spain	2.5
China	2.2
Brazil	1.7
India	0.7
World	1.75

Source: Global Footprint Network National Footprint Accounts 2019

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EARTH OVERSHOOT DAY

http://www.footprintcalculator.org/

NPTEL ONLINE CERTIFICATION COURSES

Course Name: Introduction to Environmental Engineering and Science – Fundamentals and Sustainability Concepts

Faculty Name: Dr. Brajesh Kumar Dubey

Department : Civil engineering

Topic Physical Process in Environment

Lecture 20: Mass Transport processes

Mass Transport processes

- Transport processes move chemicals from where they are generated, resulting in impacts that can be distant from the pollution sources. In addition, transport processes are used in the design of treatment systems. Here, our discussion has two purposes: to provide an understanding of the processes that cause pollutant transport and to present and apply the mathematical formulas used to calculate the resulting pollutant fluxes.

Mass Transport processes

Advection

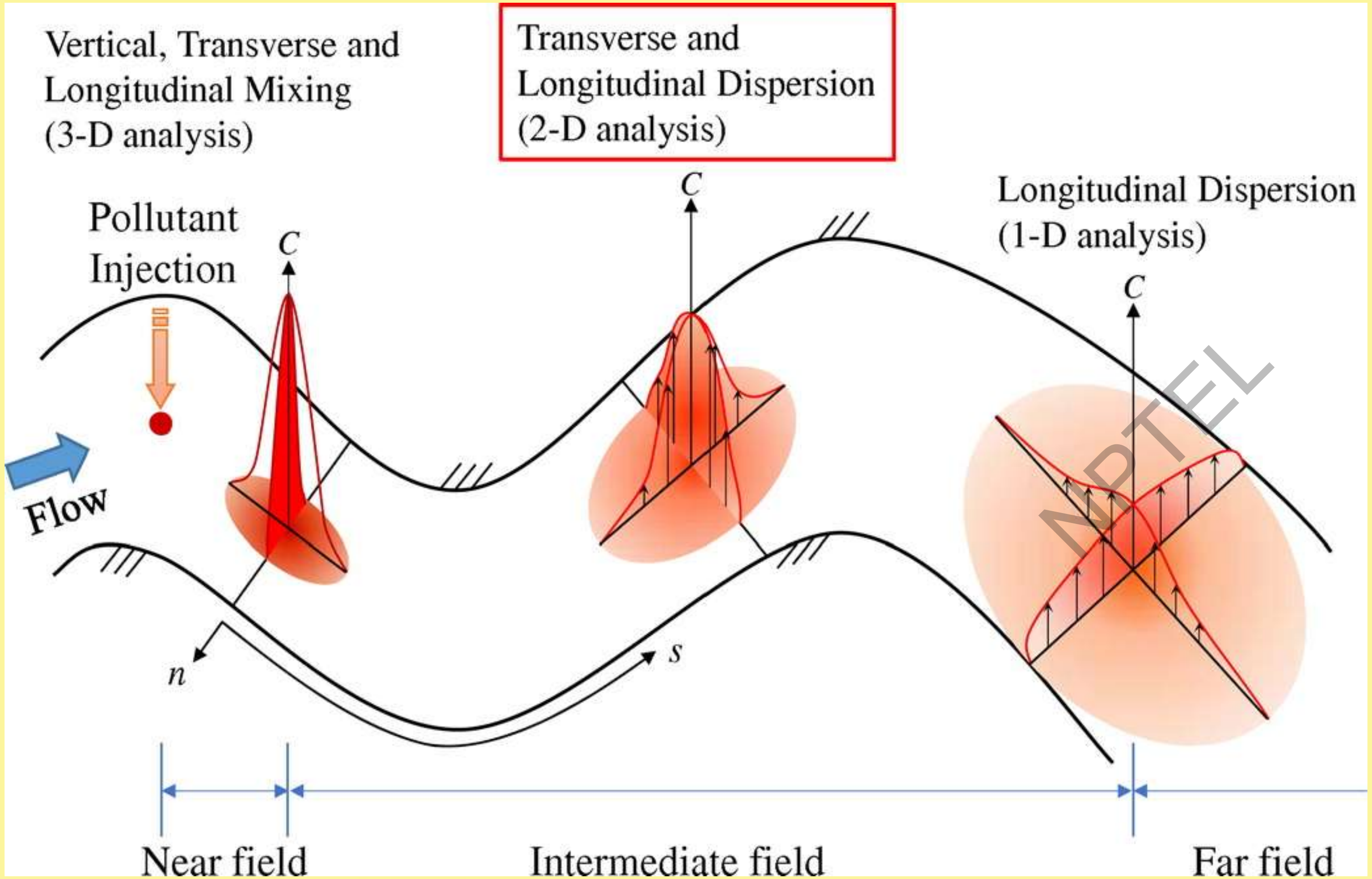
Advection refers to transport with the mean fluid flow. For example, if the wind is blowing toward the east, advection will carry any pollutants present in the atmosphere toward the east. Similarly, if a bag of dye is emptied into the center of a river, advection will carry the resulting spot of dye downstream, In contrast, dispersion refers to the transport of compounds through the action of random motions.

Mass Transport processes

Dispersion

Dispersion works to eliminate sharp discontinuities in concentration and results in smoother, flatter concentration profiles. Advective and dispersive processes usually can be considered independently.

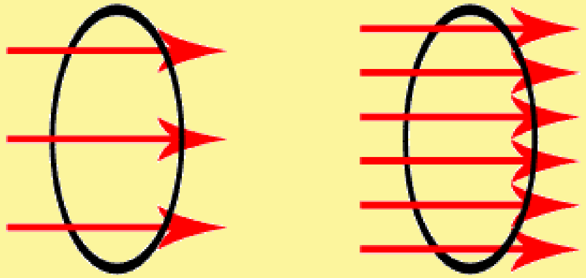
Advection and Dispersion



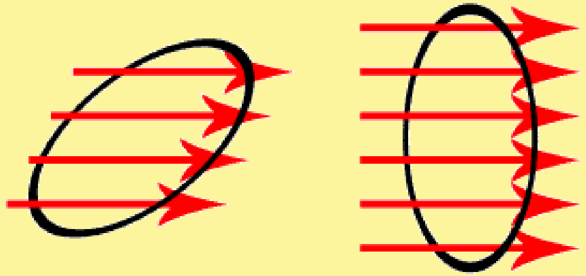
For the spot of dye in a river, while advection moves the center of mass of the dye downstream, dispersion spreads out the concentrated spot of dye to a larger, less concentrated region.

Source: Seo, I. W., Choi, H. J., Kim, Y. D., & Han, E. J. (2016). Analysis of two-dimensional mixing in natural streams based on transient tracer tests. *Journal of Hydraulic Engineering*, *142*(8), 04016020.

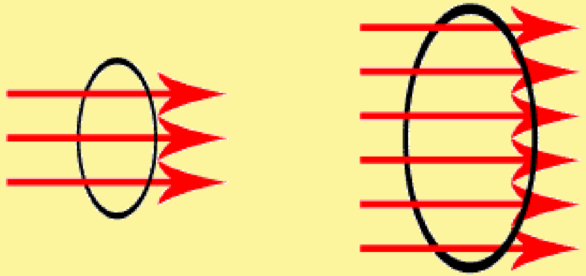
Mass Flux Density



Flux is proportional to the density of flow.



Flux varies by how the boundary faces the direction of flow.



Flux is proportional to the area within the boundary.

Mass flux density is defined as the rate of mass transferred across the plane per unit time per unit area. The symbol J will be used to represent the flux density, expressed as the rate per unit area at which mass is transported across an imaginary plane. J has units of (mass/time-length squared).

Mass Flux Density

The total mass flux across a boundary ($\dot{m}$) can be calculated from the flux density. To do this, simply multiply J by the area of the boundary:

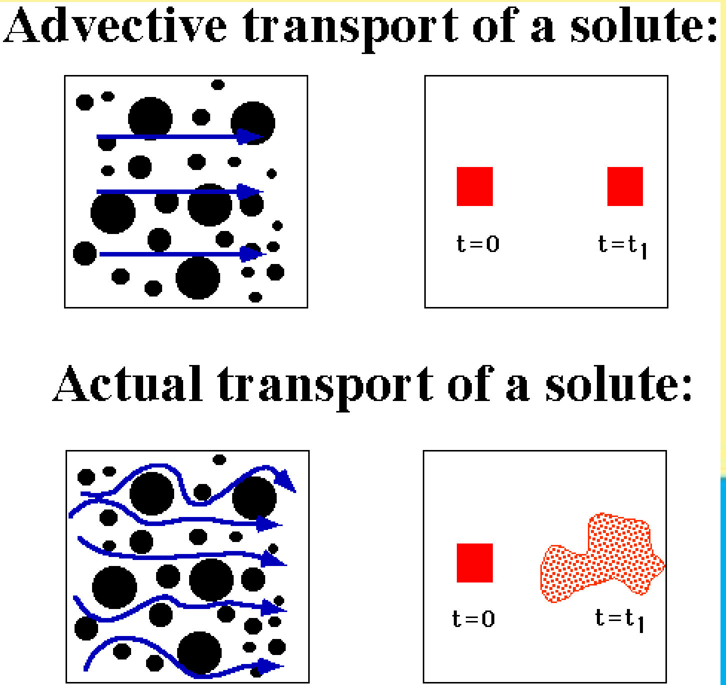
$$\dot{m} = J \times A$$

The mass transfer process that J describes can result from advection, dispersion, or a combination of both processes.

Calculation Of The Advective Flux

The advective flux refers to the movement of a compound along with flowing air or water. The advective-flux density depends simply on concentration and flow velocity:

$$J = C \times v$$



Calculation Of The Advective Flux

$$J = C \times v$$

The fluid velocity, v, is a vector quantity. It has both magnitude and direction, and the flux J refers to the movement of pollutant mass in the same direction as the fluid flow. The coordinate system is generally defined so that the ⍰- axis is oriented in the direction of fluid flow. In this case, the flux J will reflect a flux in the ⍰-direction, and the fact that J is really a vector quantity will be ignored.

Dispersion

Dispersion results from random motions of two types: the random motion of molecules and the random eddies that arise in turbulent flow. Dispersion from the random molecular motion is termed molecular diffusion; dispersion that results from turbulent eddy is called turbulent dispersion or eddy dispersion.

Example: 9

Calculate the average flux density J of phosphorus downstream at the wastewater discharge for the following conditions:

The cross-sectional area of the river is 30 m^2.

Volumetric flow rate Q = 26 m^3/s and

Downstream concentration C_d = 0.20 mg/L

The average river velocity is v = Q/A = (26 m^3/s) / (30 m^2) = 0.87 m/s.

Using the definition of flux density, we can solve for J:

$$J = [(0.20\ \text{mg/L}) \times \frac{10^3 L}{m^3}] \times (0.87\ \text{m/s})$$

$$= 174\ \text{mg}/m^2 - s \text{ or } 0.17\ \text{g}/m^2 - s$$

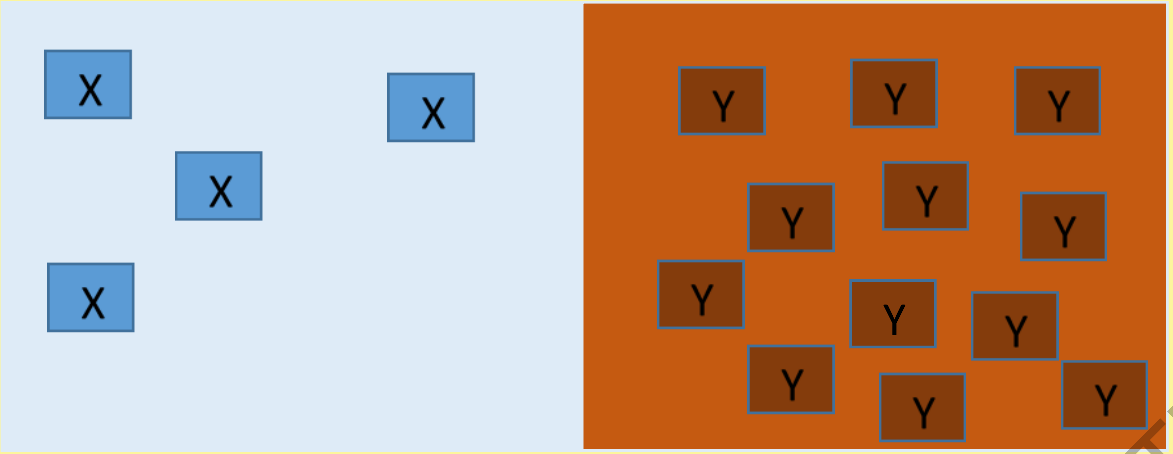
Fick’s law

Fick’s law is used to calculate the dispersive-flux density.
It can be derived by analyzing the mass transfer that results from the random motion of gas molecules.
The purpose of this derivation is to provide a qualitative and intuitive understanding of why diffusion occurs, and the derivation is useful only for that purpose.

Fick’s law

4 molecules of X

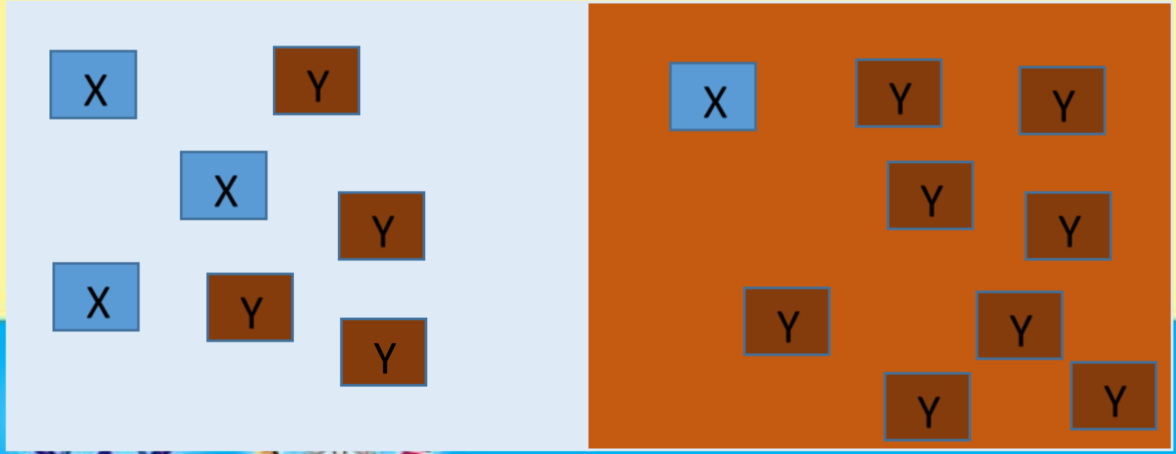
12 molecules of Y



t = 0

3 molecules of X
4 molecules of Y

1 molecules of X
8 molecules of Y



t = Δt

Fick's law

Let m_L be the total mass of molecule y in the left half of the box,

m_R equal the mass in the right half.

Our box has unit height and depth, the area perpendicular to the direction of diffusion is one square unit.

Thus, the flux density (the flux per unit area) is just equal to the rate of mass transfer across the boundary.

Fick's law

The amount of mass transferred from left to right in a single time step is equal to km_L, since each molecule has a probability k of crossing the boundary, while the amount transferred from right to left during the same period is km_R. Thus, the net rate of mass flux from left to right across the boundary is equal to $(km_L - km_R)$ divided by Δt:

$$\mathbf{J} = \frac{k}{\Delta t}(\boldsymbol{m_L} - \boldsymbol{m_R})$$

Fick's law

Since it is more convenient to work with concentrations than with total mass values, the previous equation needs to be converted to concentration units. The concentration in each half of the box is given by

$$C_L = \frac{m_L}{\Delta\chi \times (height) \times (depth)}$$

Fick's law

$$C_L = \frac{m_L}{\Delta\chi \times (height) \times (depth)}$$

Because the height and depth both equal 1, we can simplify:

$$= \frac{m_L}{\Delta x}$$

For the right side of the box,

$$C_R = \frac{m_L}{\Delta x}$$

Fick's law

$$C_R = \frac{m_L}{\Delta x}$$

Substituting $C\Delta x$ for the mass in each half of the box, we can solve for the flux density:

$$J = \frac{k}{\Delta t}(C_{\mathrm{L}}\Delta x - C_{\mathrm{R}}\Delta x)$$

$$= \frac{k}{\Delta t}(\Delta x)(C_{\mathrm{L}} - C_{\mathrm{R}})$$

Finally, note that as $\Delta x \to 0, (C_{\mathrm{R}} - C_{\mathrm{L}})/\Delta x \to dC/dx$.

Therefore, if we multiply Equation by $(\Delta x/\Delta x)$,

$$= \frac{k}{\Delta t}(\Delta x)^2(C_{\mathrm{L}} - C_{\mathrm{R}})/\,\Delta x$$

Fick's law

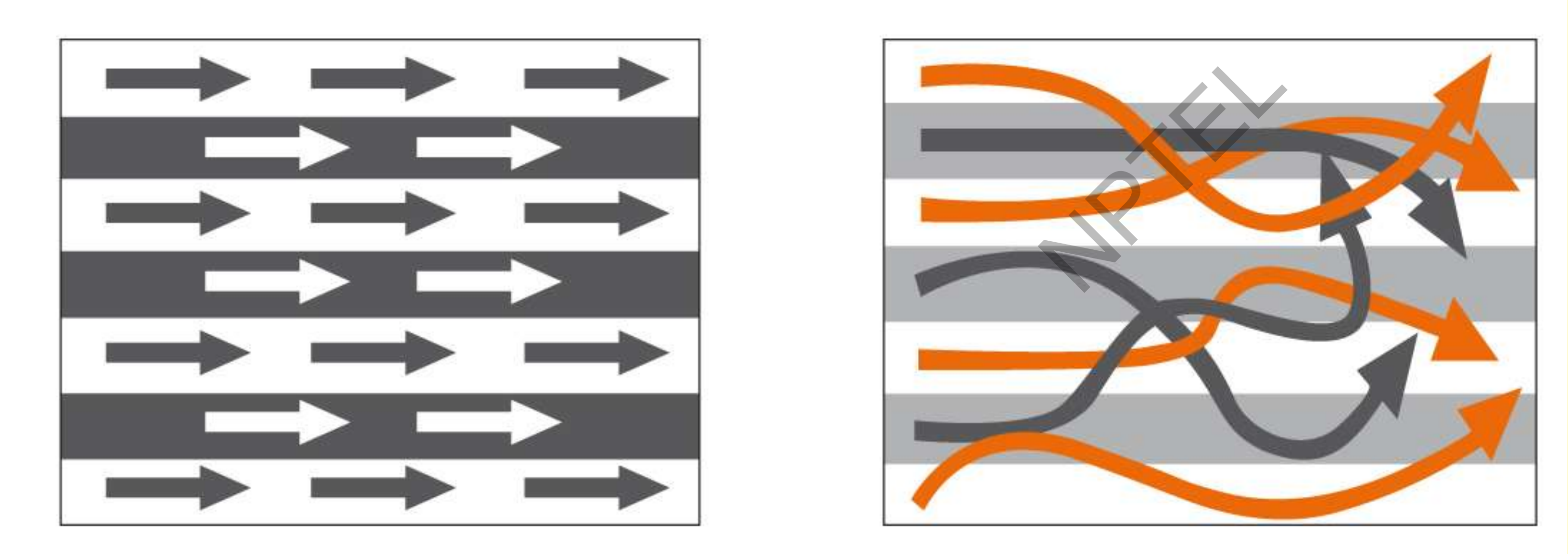
$$Finally,\ J = \frac{k}{\Delta t}(\Delta x)^2\ dC/\ \Delta x$$

J = -D dC/dX

Flux density = (constant)×(concentration gradient)

Turbulent Dispersion

Basically turbulent diffusion is due to random fluctuation in advective velocity. A typical one dimensional velocity history at a single point in a turbulent velocity field might look like the figure below.



Homogeneous flow VS Turbulent flow

Reynold’s number

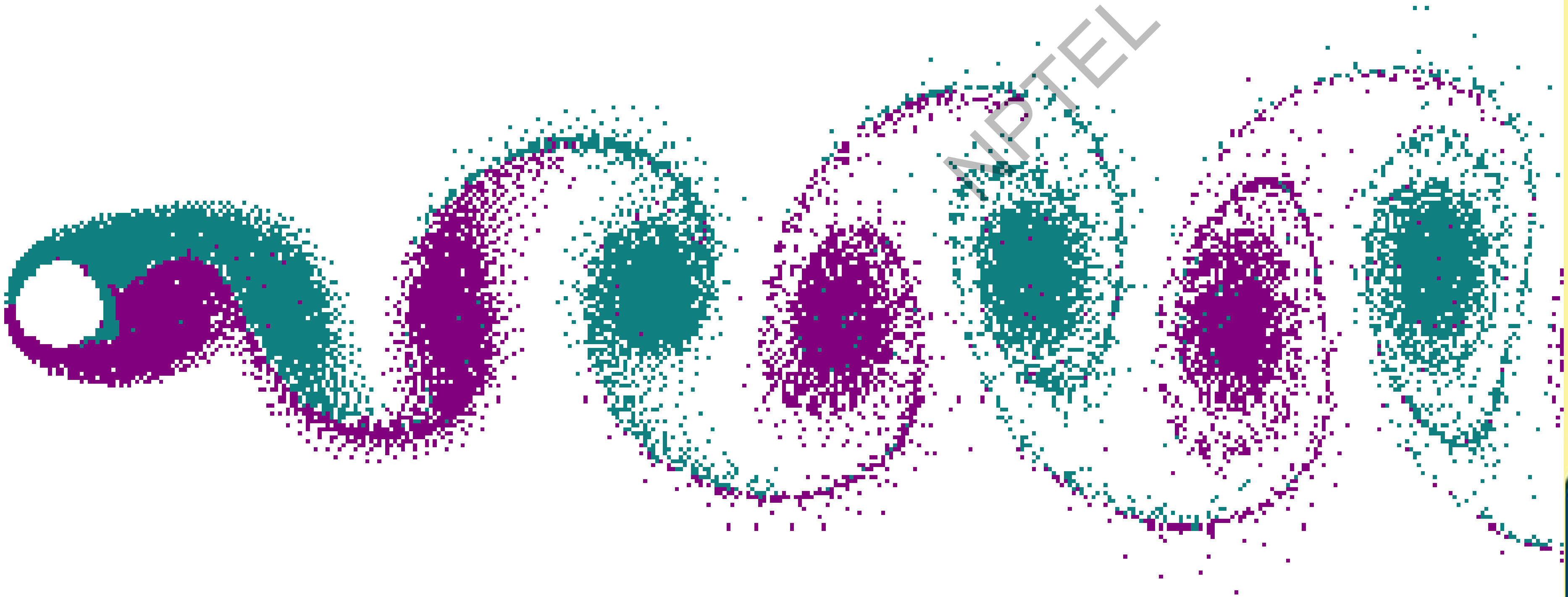
The **Reynolds number** (**Re**) is an important dimensionless quantity in fluid mechanics used to help predict flow patterns in different fluid flow situations.

At low Reynolds numbers, flows tend to be dominated by laminar (sheet-like) flow, while at high Reynolds numbers turbulence results from differences in the fluid's speed and direction, which may sometimes intersect or even move counter to the overall direction of the flow (eddy currents).

Reynold’s number

A vortex street around a cylinder.

This can occur around cylinders and spheres, for any fluid, cylinder size and fluid speed, provided that it has a Reynolds number between roughly 40 and 1000.



Reynold's number

$$Re = \frac{\text{inertia forces}}{\text{viscous forces}} = \frac{\rho \,.\, V \,.\, D}{\mu}$$

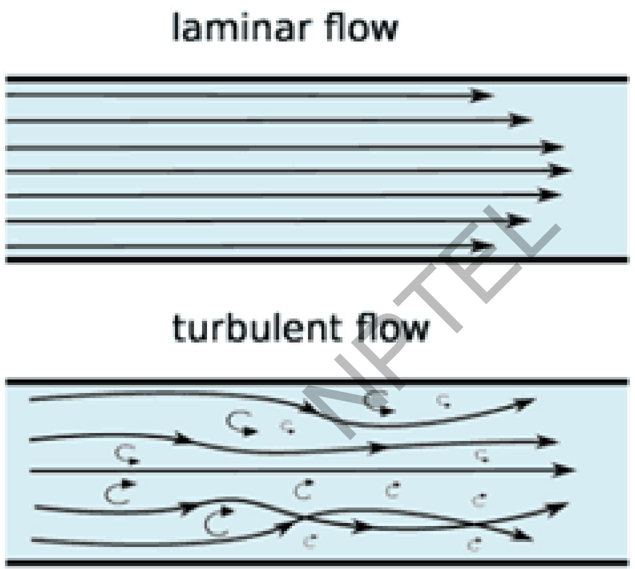
$\uparrow$ Velocity

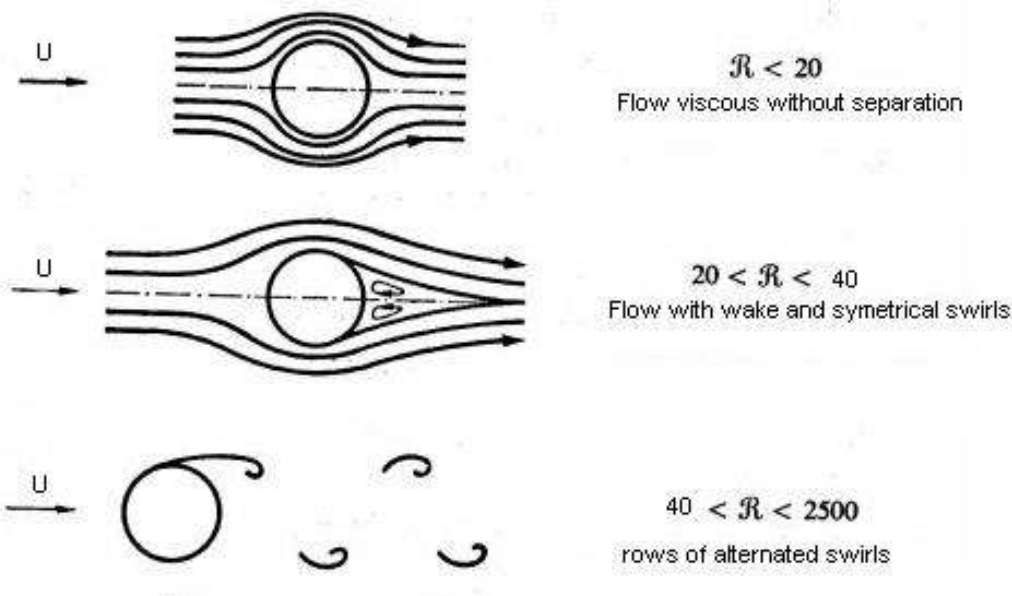
$\uparrow$ Characteristic dimension

$\uparrow$ Density

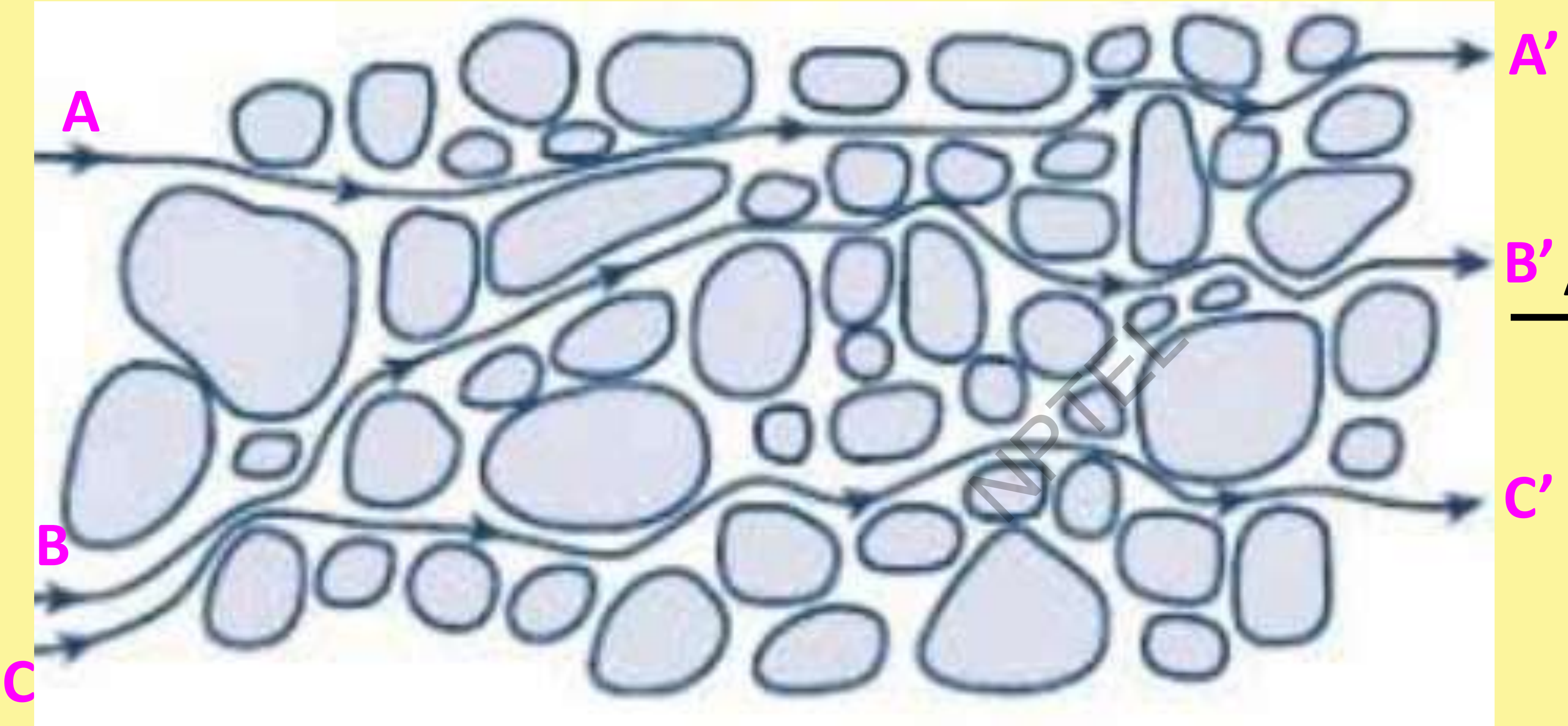
$\downarrow$ Viscosity

$\uparrow$ Re





Mechanical Dispersion

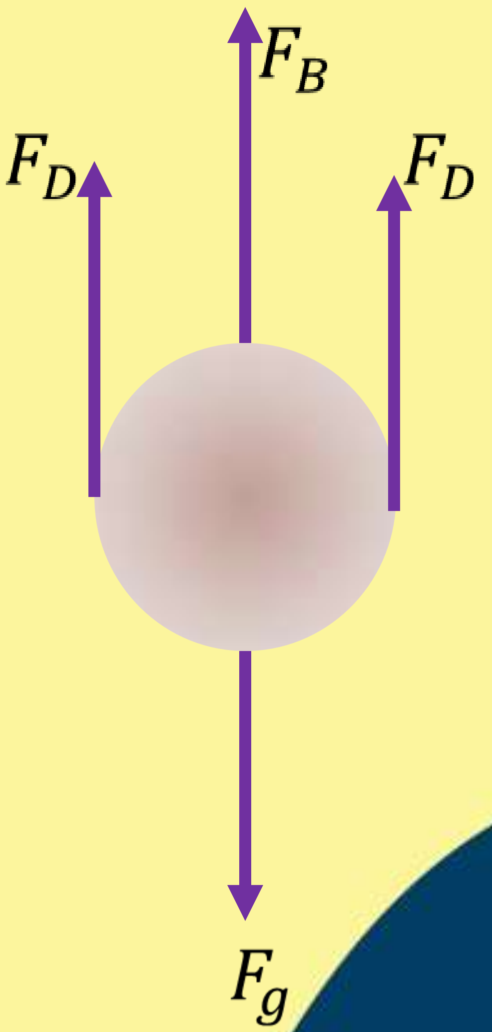


Average water flow direction

Gravitational settling

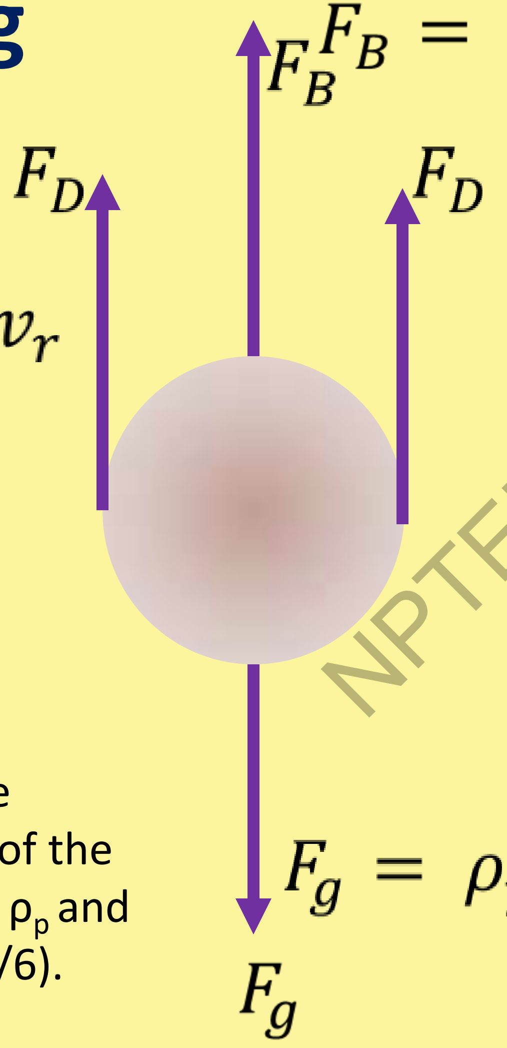
The movement of a particle in a fluid is determined by a balance of the viscous drag forces resisting the particle movement with gravitational or other forces that cause the movement.

A force balance called stokes law is used to determine the relationship between particle size and its settling velocity.



Gravitational settling

$$F_B = \rho_f \frac{\pi}{6} D_p^3 \mathrm{g}$$



$$F_D = 3\pi\mu D_p v_r$$

The buoyancy force F_B is a net upward force that results from the increase of pressure with depth within the fluid. The buoyancy force is equal to gravitational constant times the mass of the fluid displaced by the particle.

$$F_B = \rho_f \frac{\pi}{6} D_p^3 \mathrm{g}$$

Where ρ_f is the fluid density.

The gravitational force F_g, is equal to the gravitational constant g times the mass of the particle, m_p. In terms of particle density ρ_p and the diameter D_p, m_p is equal to ($\rho_p \pi D_p^3/6$).

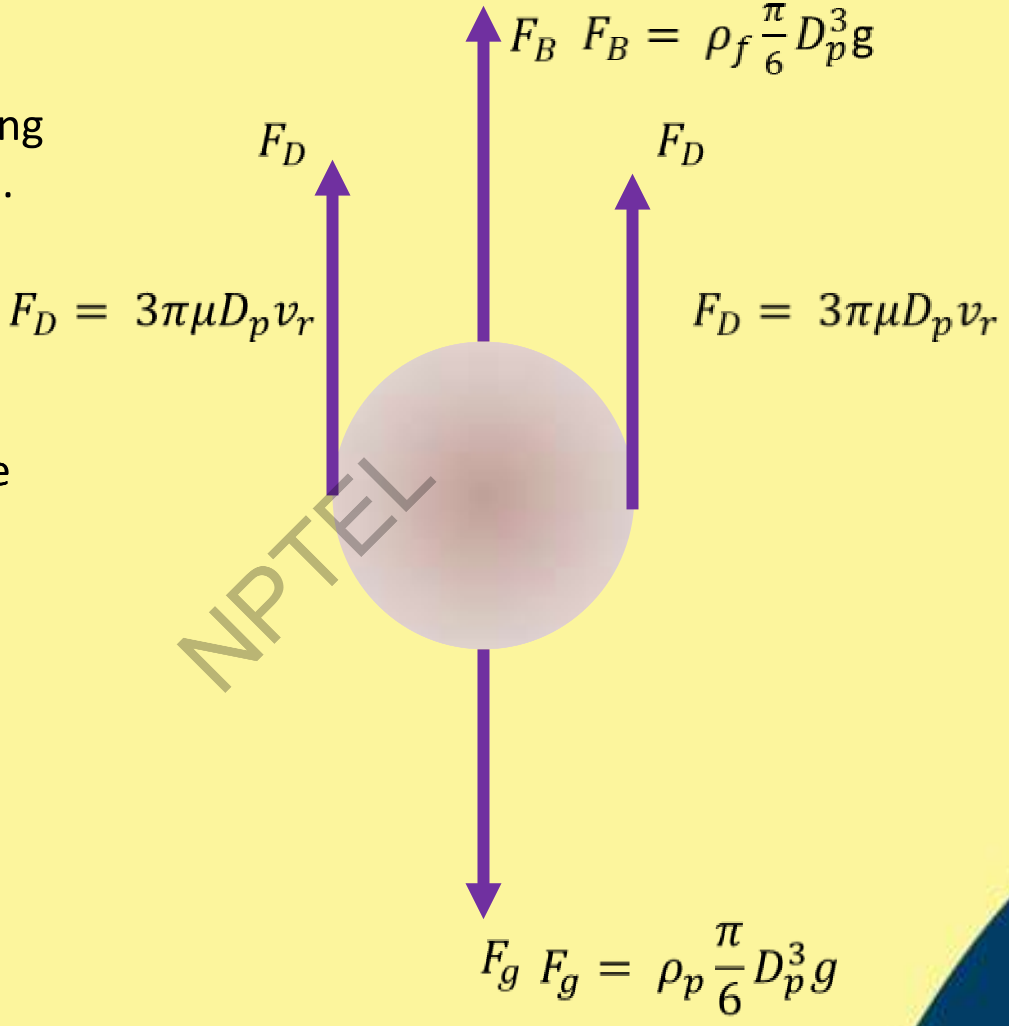
$$F_g = \rho_p \frac{\pi}{6} D_p^3 g$$

Gravitational settling

Most particle settling situations involve creeping flow conditions (Reynolds number less than 1). In this case stoke's drag force can be used as:

$$F_D = 3\pi\mu D_p v_r$$

Where µ is the fluid viscocity (units of g/cm-s) and Vr is the downward velocity of the particle relative to the fluid.



The net downward force acting on the particle is equal to the vector sum of all forces acting on the particle:

$$F_{down} = F_g - F_B - F_D$$
$$= \rho_p \frac{\pi}{6} D_p^3 g - \rho_f \frac{\pi}{6} D_p^3 g - 3\pi\mu D_p v_r$$
$$= (\rho_p - \rho_f) \frac{\pi}{6} D_p^3 g - 3\pi\mu D_p v_r$$

The particle will respond to this force according to the newton's second law. Thus,

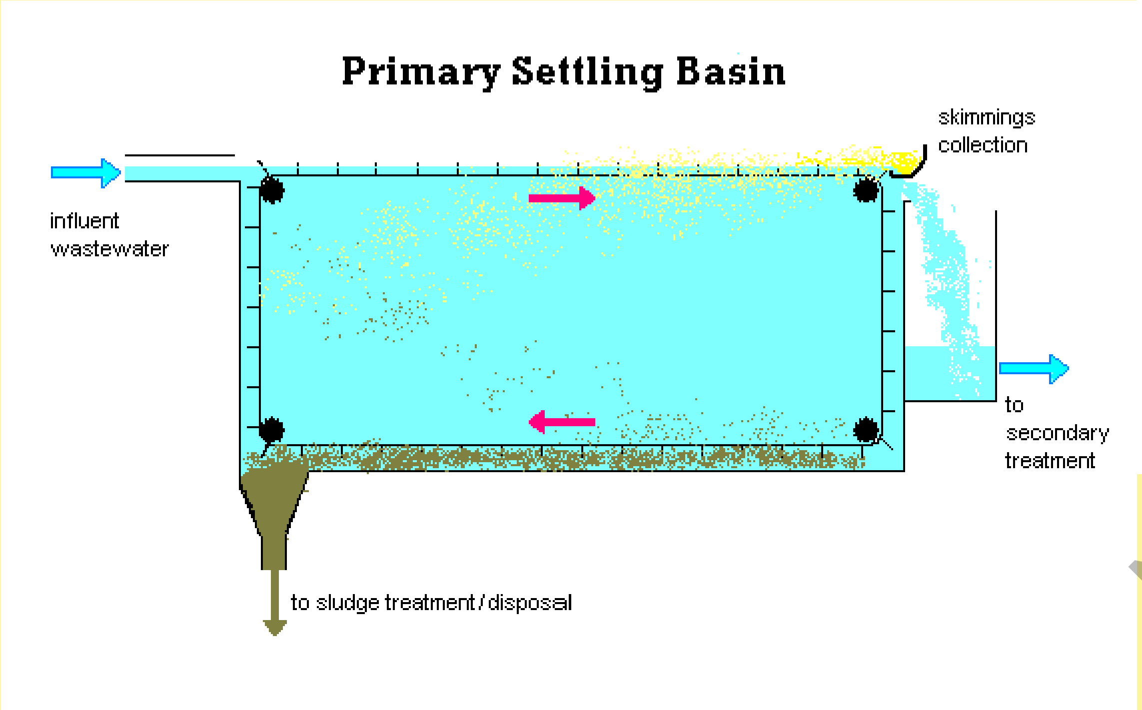
$$F_{down} = m_p \times acceleration$$
$$= m_p \times \frac{dv_r}{dt}$$

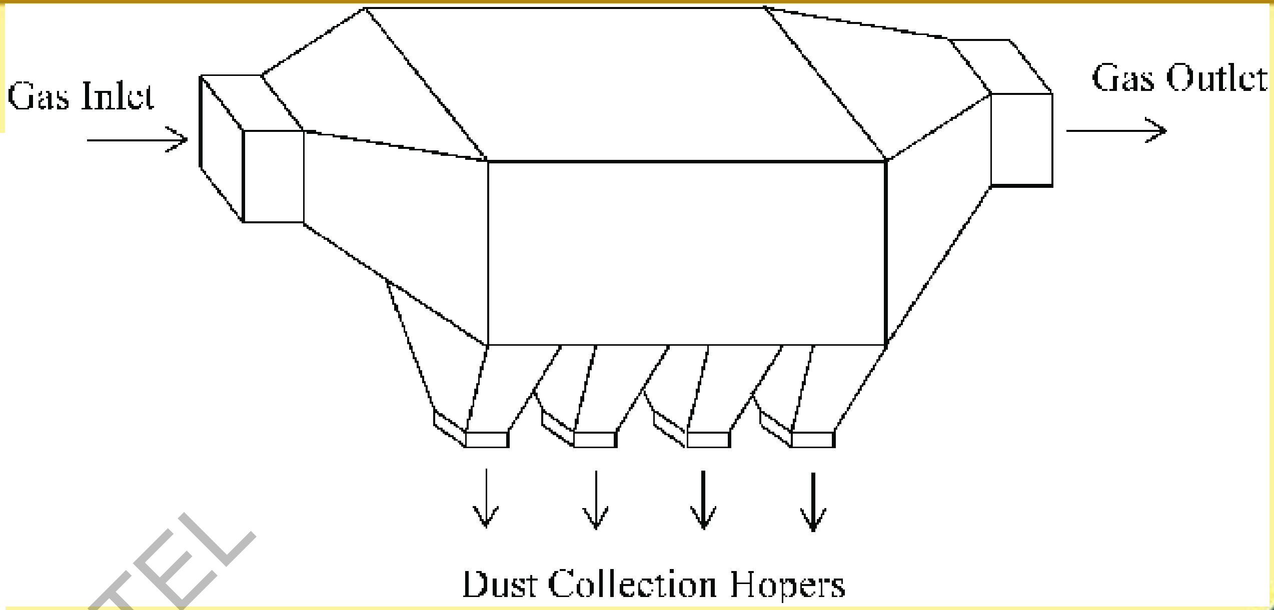
When the particle terminal velocity is reached, it is no longer accelerating so (dv/dt=0). Thus F_{down}=0 and noting that V_r is equal to the settling velocity at terminal velocity.

$$(\rho_p - \rho_f)\frac{\pi}{6}D_p^3 g = 3\pi\mu D_p v_s$$

$$\boxed{v_s = \frac{g(\rho_p - \rho_f)}{18\mu}D_p^2}$$

Gravitational settling





Conclusion

Conclusion:

In this chapter, readers become learn about the physical processes that are important in the movement of pollutants through the environment and processes used to control and treat pollutant. The week begins with material balance. Then the reactor configurations are discussed. The final section of this week discuss about energy balance and mass transport process.