Transport Phenomena in Biomedical Engineering (196 C)

DATES: January 28 to May 20, 2008
TIMES: 6:00-8:45 PM
ROOM: 333
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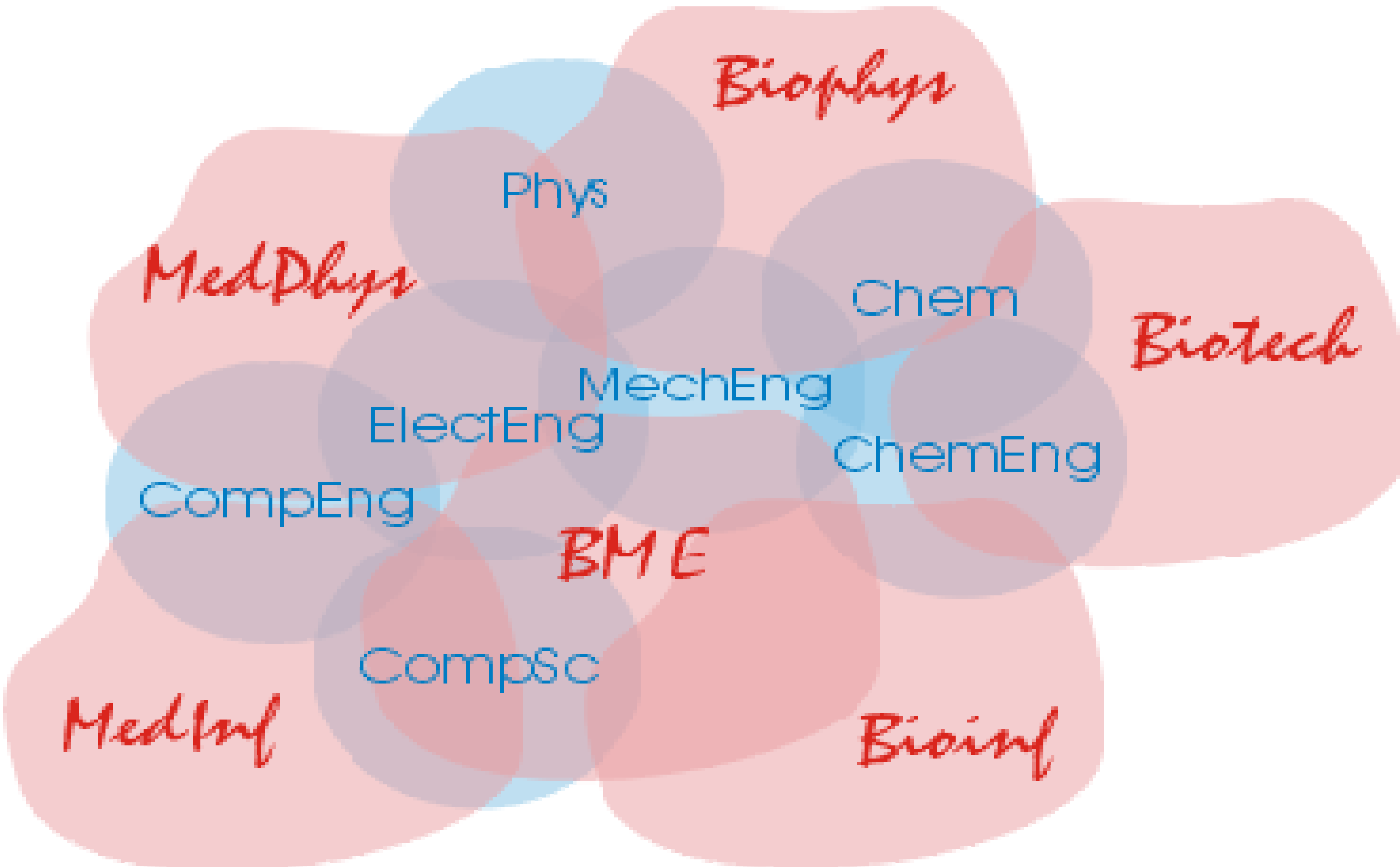
Course Syllabus

- Please refer to Handout
- Link for the guidelines of the Poster Presentation given during lecture #2.
- Link for the solutions to assignments and tests posted given during lecture #2.

What is Biomedical Engineering?

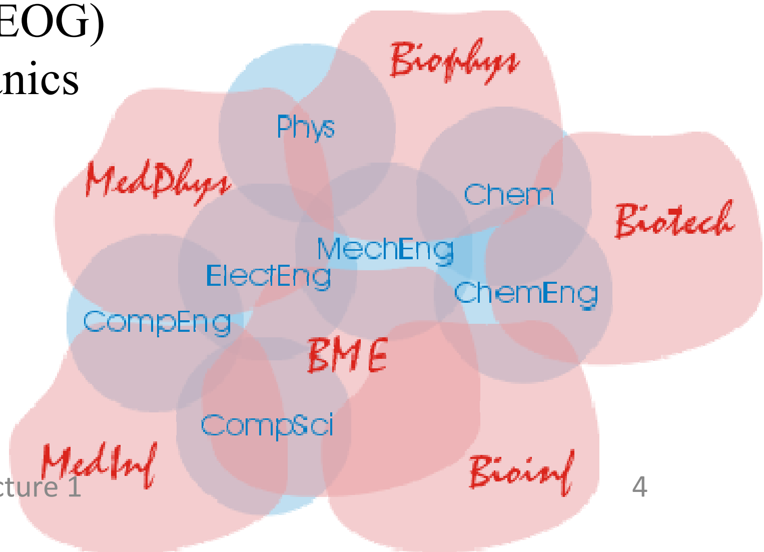


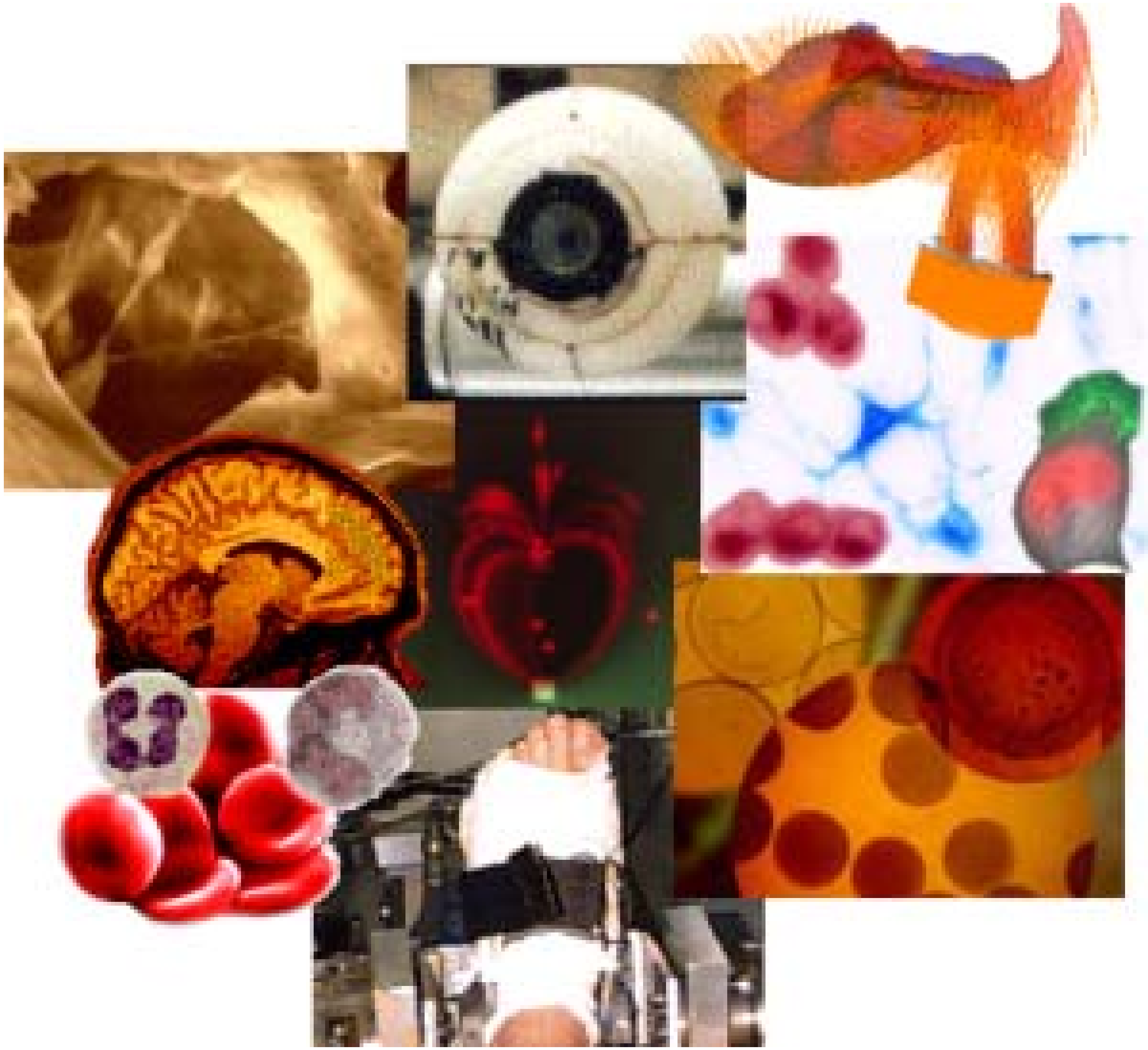
What is Biomedical Engineering?

• Biomedical Engineering may be defined as the application of Engineering to Medicine and Life Sciences.

• Many fields of research have already reached the commercialization stage:

❖Biomaterials, including Artificial Cells and Organs Engineering
❖Medical Imaging, Image Processing, Feature Extraction in Genomics and Proteomics
❖Signal Analysis for brain (EEG), muscles (EMG), eyes (EOG)
❖Biomechanics , including orthopedic and auditory mechanics





What is Transport Phenomena?

A **transport phenomenon** is any of various mechanisms by which particles or quantities move from one place to another. The laws which govern transport connect a flux (amount that flows through a unit area per unit time) with a "motive force".

rate of transfer process = driving force/resistance

There are three main categories of transport phenomena with their respective driving forces:

- Heat transfer (conduction, convection, radiation) (ΔT and heat transfer coefficients)
- Mass transfer (diffusion, osmosis) (ΔC and Mass Transfer coefficients)
- Fluid dynamics (or momentum transfer) / (ΔP and Momentum Transfer coefficients)

It is important to note that in molecular transport, heat, or mass there are many similarities. The molecular diffusion equations of Newton for momentum, Fourier for heat, and Fick for mass are very similar.

Many Biomedical engineering problems require the mathematical equations for the Heat, Mass and Momentum Balance to be solved simultaneously.

Why Do We need Transport Phenomena?

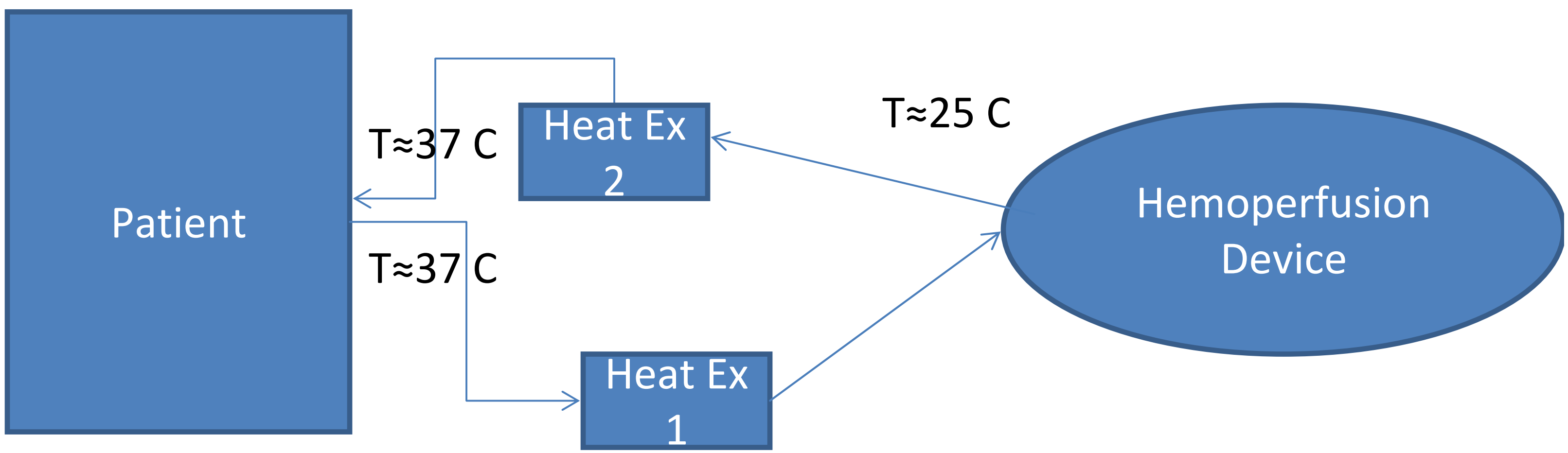
- The laws of Thermodynamics only treat systems that are in equilibrium. They can predict the amount of energy required to change from one equilibrium state to another but they cannot predict how fast these changes will occur.

- Transport Phenomena and Reaction Kinetics supplement the laws of Themodynamics by providing methods of analyses that can be used to predict rates of energy transfer real-time.

Hemoperfusion Example

• At equilibrium, the amount of heat needed to keep the blood temperature constant based on the Thermodynamics(Cp, Tambient) is 10 W.

• It will take 2 minutes after hemoperfusion for the patient's blood to reach 37 ◦C is sufficient energy is applied.



Tools

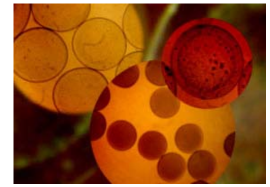
- Mathematical Methods:
- ❖ Linear and Non-Linear Differential Equations
- ❖ Boundary Value Problems

- Software:
- ❖ Mathematical Software (Mathematica, Matlab, …)
- ❖ Transport Phenomena Software (Radtherm, CFD, Flowtherm, Intellisense,…)

- Dimensional Analysis:
- ❖ In some situations it is not possible to integrate the equations .
- ❖ The Buckingham pi theorem determines the number of dimensionless groups into which the equation variables could be combined.
- ❖ $N_{Re} = (\rho v D/\mu)$; The Reynolds number is defined as the ratio of inertia to viscous forces.
- ❖ $N_{Fo} = (\alpha t/L^2)$; The Fourier number is defined as the ratio of heat conduction to storage of heat

Instructor's Experience in BioEngineering

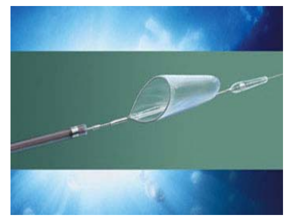
- Graduate School (8 years): Hemoglobin Microencapsulation and Suspension Stabilization by Bio-Polymer Adsorption.



Thermodynamics, Biomaterials,

Reaction Kinetics, Heat Transfer, Mass Transfer, Mathematical Simulation

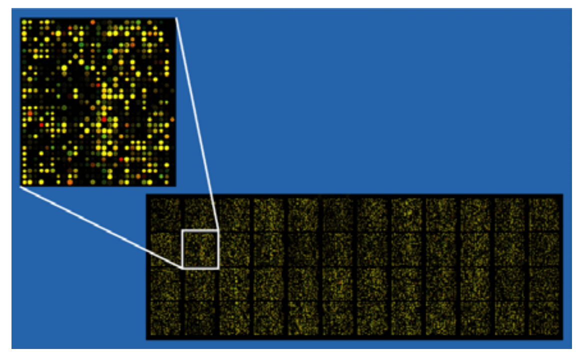
- Diagnostics, Microfludics and Medical Device (5 years)



Reaction Kinetics, Heat & Mass and Momentun

Transfer, Statistical Simulation

- Genomics, Scale-up of Micro-Array Production (6 years)



Reaction Kinetics, Mass and Momentun Transfer, Statistical

Simulation

REVIEW OF BASIC CONCEPTS

UNITS AND DIMENSIONS

- In order to avoid serious errors in calculations if the same system of units is not used throughout the calculation stage.

- Various conversion tables exist to relate the SI (Systeme International) to the English, American and the cgs systems.

EXAMPLE

Conversion Formulas

- *a* °C = (4/5)*a* °Réaumur = [32 + (9/5)*a*] °F *b* °Réaumur = (5/4)*b* °C = [32 + (9/4)*b*] °F
- *c* °F = (5/9)(*c* - 32) °C = (4/9)(*c* - 32) °Réaumur
- *t* °C = (*t* + 273.15) K
- T_K K = (T_K - 273.15) °C = [1.80 * (T_K - 273.15) + 32] °F = 1.80 T_K °Rankine

Fundamental Dimensions

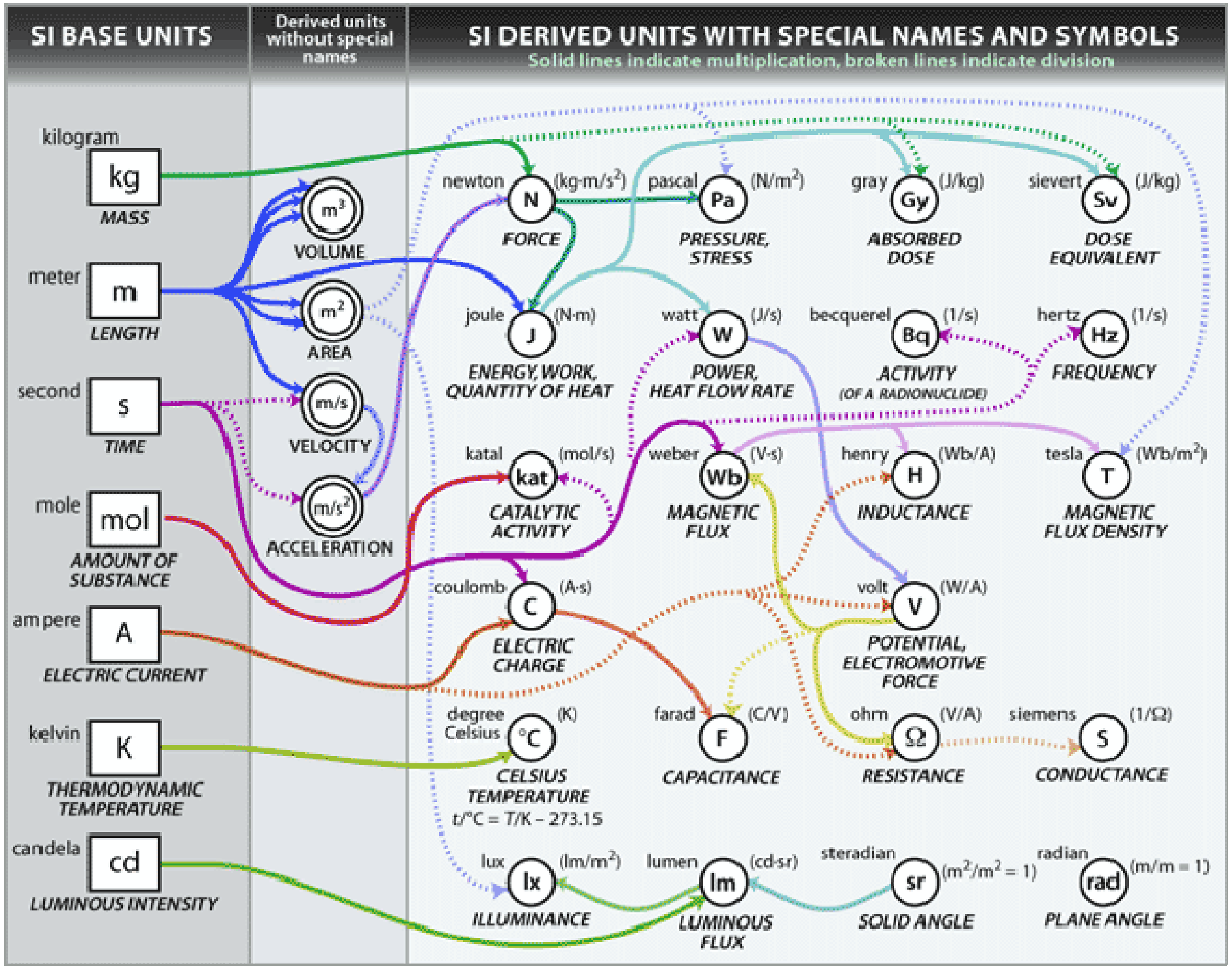
Fundamental dimension	Unit	Abbreviation
length	meter	m
mass	kilogram	kg
time	second	s
electrical **current**	ampere	A
temperature	Kelvin	K
amount	**mole**	mol
luminous intensity	**candela**	cd

The measurement of the physical properties derive from seven fundamental dimensions.

Prefix of Units

Multiplier	Size*	Name	Abbrev.
10^{18}	quintillion	exa	E
10^{15}	quadrillion	peta	P
10^{12}	trillion	tera	T
10^{9}	billion	giga	G
10^{6}	million	mega	M
10^{3}	thousand	kilo	k
10^{-3}	thousandth	milli	m
10^{-6}	millionth	micro	μ
10^{-9}	billionth	nano	n
10^{-12}	trillionth	pico	p
10^{-15}	quadrillionth	femto	f
10^{-18}	quintillionth	atto	a

FUNDAMENTAL UNITS AND DERIVED UNITS



EQUATION OF STATE

- An equation of state is a mathematical expression that relates the pressure, volume, and temperature of gas, liquid or solid.
- The Ideal, Van der Waal, Berthelot equations are some examples.
- The ideal gas is given by the following relationship:

$$PV = nRT$$

P denotes the absolute pressure, V is the volume, T is the absolute temperature and n the number of moles. R is called the universal gas constant.

Conversion Problem

Calculate the volume (m^3) occupied by 100 lbm of oxygen (Mw=0.032 kg/mole) at a pressure* of 40 feet of water and a temperature of 20◦C.

$$V = \left(\left(100\ lbm \times \frac{1 kg}{2.2046\ lbm} \times \frac{1\ mole}{0.032\ kg} \right) \times 8.314 \frac{m^3 Pa}{mole K} \times (273.15 + 20)\ K \right)$$

$$\times \frac{1}{\left(40\ ft\ of\ water \times \frac{1 atm}{33.91\ ft\ of\ water} \times \frac{101{,}325\ Pa}{1\ atm} \right)} = 28.90\ m^3$$

* Absolute pressure = (gauge pressure) + atmospheric pressure

General Property Balance

(rate of input) = (rate of output) + (rate of accumulation) – (rate of generation) + (rate of consumption)

@ Steady State

(rate of input) = (rate of output)

The laws for the conservation of mass, energy, and momentum are all stated in terms of a system. A system is defined as a collection of fluid of fixed identity. The method used it to select a control volume, which is a region fixed in space through which the fluid flows.

Degrees of Freedom

- D*egrees of freedom* are used to determine if a material balance is possible for a given process. It takes into account the number reactions, temperature, pressure, heat transfer, percent yield, moles entering/exiting, and various other pieces of additional information.

- Degrees of Freedom = Number of Unknowns – Number of Equations

- Typically we have more unknowns than equations. These unknowns become design variables or quantities to be specified.

EXAMPLE: Glucose Fermentation

$C_6H_{12}O_6$ + a NH_3 → $bCH_{1.74}N_{0.2}O_{0.45}$ (yeast) + cC_2H_5OH + d $C_3H_8O_3$ + e CO_2+ fH_2O

Constraints: d=0.12 c and f=0.08 d

How many variables?

How many equations?

How many degrees of freedom?

Solution

- 6 variables (a,b,c,d,e,f)

$C_6H_{12}O_6 + a\ NH_3 \Longrightarrow bCH_{1.74}N_{0.2}O_{0.45}$ (yeast) $+ cC_2H_5OH + d\ C_3H_8O_3 + e\ CO_2 + fH_2O$

- 6 equations (matrix solution)

C balance: $6 = b + 2c + 3d + e$

H balance: $12 + 3a = 1.74b + 6c + 8d + 2f$

O balance: $6 = 0.45b + c + 3d + 2e + f$

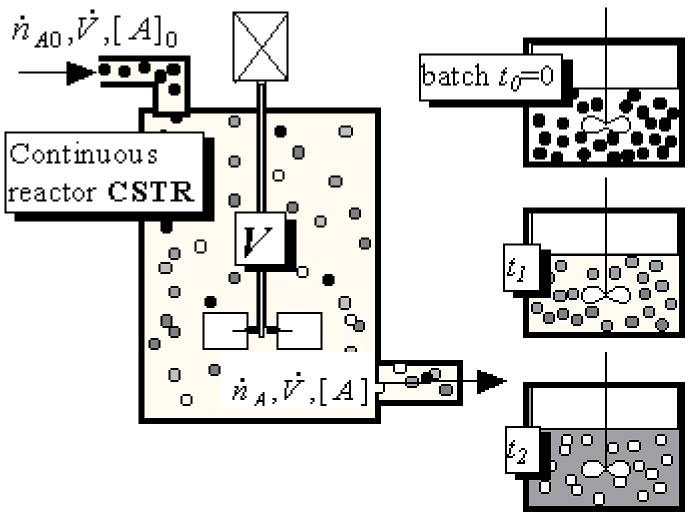
N Balance: $a = 0.2b$

Constraints: $d=0.12\ c$ and $f=0.08\ d$

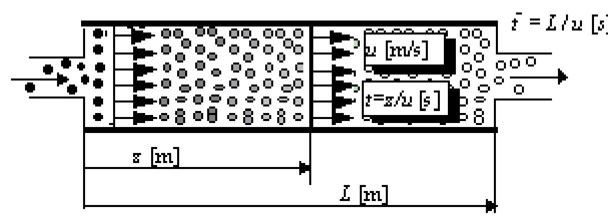
- No degrees of freedom

Mass Balances for the Ideal Type Reactors

- In Chemical Engineering there are 3 ideal types of reactors: CSTR , Batch and Plug Flow. A reaction can use multiple reactor types in series.
- CSTR : Dialysis and Hollow Fiber reactors.
- Batch: Fermentation and Polymerization
- Plug Flow: Drug Distribution in the Body



Plug Flow



Mass Balance Equations for a CSTR

- CSTR stands for Continuously Stirred Tank Reactor. In which ideally perfect mixing occurs independent of the control volume.
- For Steady State (no accumulation) , the mass balance for reactant A is:

$$F_{in} c_{Ain} - F_{out} c_{Aout} = -r_A V$$

$$\frac{V}{F} = \theta$$

$$r_A V = \frac{dc_A V}{dt}$$

r_A: Intrinsic rate of production (generation)
V: Reactor Volume
F: Volumetric Flowrate
C_A: Concentration of reactant A
θ: Residence Time

Mass Balance Equations for a Batch Reactor

- The assumption in a batch reactor is that the yield is a function of reaction time and independent of control volume.
- Since there are no feed or exit streams only the generation and accumulation terms exist. For Steady State (no accumulation) , the mass balance for reactant A is:

$$r_A V = \frac{dc_A V}{dt}$$

r_A: Intrinsic rate of production (generation)
V: Reactor Volume

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

constant volume assumption

Mass Balance Equations for a Plug Flow or Tubular Reactor

- The ideal plug flow reactor is one in which there is no mixing in the direction of flow and complete mixing in the direction perpendicular to the flow.
- Plug flow reactors are usually operated as steady state so that the properties are constant with respect to time.

$$F_{in} C_A \Big|_v = F_{out} C_A \Big|_{v+\Delta v} - r_A \Delta V$$

$$As \quad \Delta V \to 0$$

$$\frac{d(FC_A)}{dV} = r_A$$

$$When \ Fin = Fout$$

$$r_A = \frac{dC_A}{d\left(V/F\right)} = \frac{dC_A}{d\theta}$$

r_A: Intrinsic rate of production (generation)
V: Reactor Volume
F: Volumetric Flowrate
C_A: Concentration of reactant A
θ: Residence Time