Environmental Bioprocesses Engineering

Marc Deront

marc.deront@epfl.ch

ENAC-LBE

Lab. de Biotechnologie Environnementale

based on lecture from Sirous Ebrahimi (sirous.ebrahimi@epfl.ch)

What do you learn in this course?

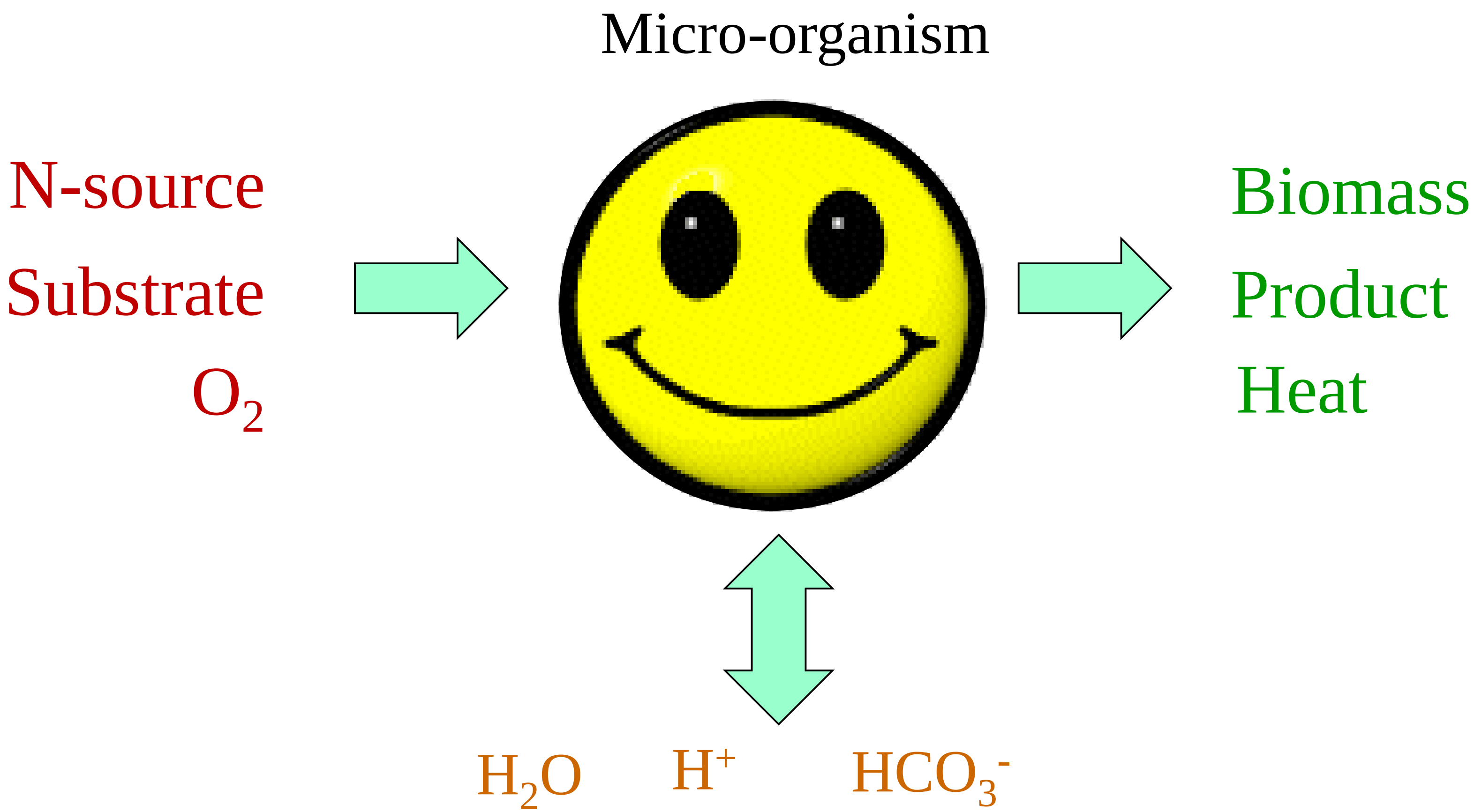
You will learn the ***engineering tools*** *you need as a* ***bioprocess engineer***

What are the tools?

The ways to calculate microbial rates

Quantification of Microbial Rates

Consumption or Production



Quantification of Microbial Rates

Consumption or Production

?

Rates of consumption or production are obtained from

Mass balances

Over reactor, for **each compound** and from measured:

1. Volumes
2. Concentrations
3. Flow rates

Mass Balances over reactors

Accumulation = Transports + Conversions

Transport rate IN TO the system (+)
or
Transport rate OUT OF the system (-)

rate of PRODUCTION (+)
or
rate of CONSUMPTION (-)

Accumulation [amount/h] = In [amount/h] – Out [amount/h] + Conversions [amount/h]

For each compound C_i in the biosystem:

$$Accumulation_i = \sum R_i^{IN} - \sum R_i^{OUT} + \sum R_i^{Conversions}$$

Important: At Steady State, Accumulation = 0

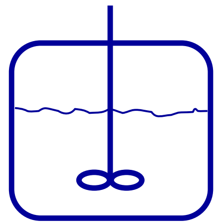
Mass Balances over reactors

$$Accumulation_i = \sum R_i^{IN} - \sum R_i^{OUT} + \sum R_i^{Conversions}$$

Accumulation = 0, at Steady State

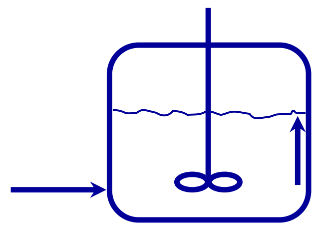
3 types of bioreactor

Batch



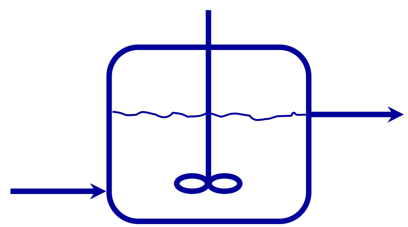
Transport IN = 0
Transport OUT = 0
Accumulation = Conversion

Fed batch



Transport OUT = 0
Accumulation = In + Conversion

Chemostat



Accumulation = 0
(at steady state)
IN – OUT + Conversion = 0

Rates from Mass Balances

How are rates defined? (1)

Consider 2 chemostats where microorganism consumes glucose

$$Accumulation_i = \sum R_i^{IN} - \sum R_i^{OUT} + \sum R_i^{Conversions}$$

[amount.hr^{-1}],[kg.hr^{-1}] or [mole.hr^{-1}]

Reactor 1 (Micro-organism 1)

- Inlet: 0.1 m^3.hr^{-1}, 40.1 kg S.m^{-3}
- $V_{reactor}$ = 2 m^3
- 20 kg biomass.m^{-3}
- Outlet: 0.1 m^3.hr^{-1}, 0.1 kg S.m^{-3}

Microorganism 1

0.1∗40.1 – 0.1∗0.1 + conversion rate = 0

Mass rate = R_S = - 4 kgS.hr^{-1}

Reactor 2 (Micro-organism 2)

- Inlet: 1.2 m^3.hr^{-1}, 3.83 kg S.m^{-3}
- $V_{reactor}$ = 5 m^3
- 2 kg biomass.m^{-3}
- Outlet: 1.2 m^3.hr^{-1}, 0.5 kg S.m^{-3}

Microorganism 2

1.2∗3.83 – 1.2∗0.5 + conversion rate = 0

Mass rate = R_S = - 4 kgS.hr^{-1}

Same rates, but not same reactors?

Rates from mass balance

How are rates defined? (2)

Reactor (2) is bigger than (1)!
More expensive…

r_i Volumetric rate = R_i / $V_{reactor}$

[amount.m^{-3}.hr^{-1}],[kg.m^{-3}.hr^{-1}] or [mole.m^{-3}hr^{-1}]

Reactor (1) — Micro-organism 1

Inflow: 0.1 m^3.hr^{-1}, 40.1 kg S.m^{-3} → (1) $V_{reactor}$ = 2 m^3, 20 kg biomass.m^{-3} → Outflow: 0.1 m^3.hr^{-1}, 0.1 kg S.m^{-3}

Microorganism (1)

Mass rate = R_S = - 4 kgS.hr^{-1}

Volumetric rate r_S = R_S / 2 = - 2 kgS.m^{-3}.hr^{-1}

Reactor (2) — Micro-organism 2

Inflow: 1.2 m^3.hr^{-1}, 3.83 kg S.m^{-3} → (2) $V_{reactor}$ = 5 m^3, 2 kg biomass.m^{-3} → Outflow: 1.2 m^3.hr^{-1}, 0.5 kg S.m^{-3}

Microorganism (2)

Mass rate = R_S = - 4 kgS.hr^{-1}

Volumetric rate r_S = R_S / 5 = - 0.8 kgS.m^{-3}.hr^{-1}

Reactor (1) seems the best !

Rates from mass balance

How are rates defined? (3)

But who do the job? Microorganisms!!!

- Do both microorganisms have equal rates?
- How fast do they "work"?

q_i Specific rate = R_i / Biomass amont

q_i Specific rate = r_i / Biomass concentration

[amount S.amount $X^{-1}.h^{-1}$],[kgS.kg$X^{-1}.h^{-1}$] or [moleS.mole$X^{-1}.h^{-1}$]

(1) $V_{reactor} = 2\ m^3$

20 kg biomass.m^{-3}

Microorganism (1)

Mass rate = R_S = - 4 kgS.hr^{-1}

Volumetric rate $r_S = R_S$ / 2 = - 2 kgS.$m^{-3}.hr^{-1}$

Specific rate $q_S = R_S$ / (2 . 20) = - 0.1 kgS.kg$X^{-1}.hr^{-1}$

Specific rate $q_S = r_S$ / (20) = - 0.1 kgS.kg$X^{-1}.hr^{-1}$

(2) $V_{reactor} = 5\ m^3$

2 kg biomass.m^{-3}

Microorganism (2)

Mass rate = R_S = - 4 kg.hr^{-1}

Volumetric rate $r_S = R_S$ / 5 = - 0.8 kg.$m^{-3}.hr^{-1}$

Specific rate $q_S = R_S$ / (5 . 2)= - 0.4 kgS.kg$X^{-1}.hr^{-1}$

Specific rate $q_S = r_S$ / (2)= - 0.4 kgS.kg$X^{-1}.hr^{-1}$

Microorganism (2) is 4 times more efficient than microorganism (1) !

Three types of rates

R_i : Mass Rate — amount of C_i per hour — R_i: $kgC_i.hr^{-1}$

r_i : Volumetric rate — $\dfrac{\text{amount of } C_i \text{ per hour}}{m^3 \text{ reactor}}$ — r_i: $kgC_i \,.\, m^{-3}.\, hr^{-1}$

q_i: Specific rate — $\dfrac{\text{amount of Ci per hour}}{\text{amount of micro-org.}}$ — q_i: $kgC_i.kgX^{-1}.hr^{-1}$

$$R_i = r_i \times V_r$$

$$\text{amount/hour} = \frac{\text{amount / hour}}{m^3 \text{ reactor}} \times m_3 \text{ reactor}$$

$$r_i = q_i \times C_X$$

$$\frac{\text{Amount/hour}}{\text{m3 reactor}} = \frac{\text{amount/hour}}{\text{kg X}} \times \frac{\text{kg X}}{m^3 \text{ reactor}}$$

For each compound:

substrate	$(-r_S)$	=	$(-q_S)\ C_X$	
oxygen	$(-r_{O2})$	=	$(-q_{O2})\ C_X$	
biomass	r_X	=	$q_X\ C_X$	$= \mu\ C_X$
C_{O2}	r_{CO2}	=	$q_{CO2}\ C_X$	
product	r_P	=	$q_P\ C_X$	

Yield = ratio of rates

Definition of yield $\mathbf{Y_{ij}}$ of compound **j** over **i** :

$$Y_{ij} = \left|\frac{rate_j}{rate_i}\right| = \left|\frac{R_j}{R_i}\right| = \left|\frac{R_j / V_R}{R_i / V_R}\right| = \left|\frac{r_j}{-r_i}\right| = \left|\frac{q_j . C_X}{q_i . C_X}\right| = \left|\frac{q_j}{q_i}\right|$$

Often, yields are related to biomass growth rate i.e $\mathbf{Y_{ix}}$

$$Y_{SX} = \left|\frac{r_X}{-r_S}\right| = \left|\frac{\mu . C_X}{-q_S . C_X}\right| = \left|\frac{\mu}{-q_S}\right|$$

But all $\mathbf{Y_{ij}}$ yields can be obtained with $\mathbf{Y_{ix}}$ yields

$$Y_{SP} = \left|\frac{q_P}{-q_S}\right| = \left|\frac{q_P / \mu}{-q_S / \mu}\right| = \left|\frac{1 / Y_{PX}}{1 / Y_{SX}}\right| = \left|\frac{Y_{SX}}{Y_{PX}}\right|$$

Yield = ratio of rates

$$Y_{SX} = \left|\frac{r_X}{-r_S}\right| = \left|\frac{\mu . C_X}{-q_S . C_X}\right| = \left|\frac{\mu}{-q_S}\right| = 1/Y_{XS}$$

From your background

$$\left\{ q_S = q_S^{max} . \frac{C_S}{k_S + C_S} \right\} \xleftarrow{Y_{XS}} \div \xrightarrow{Y_{SX}} \left\{ \mu = \mu^{max} . \frac{S}{k_S + S} \right\}$$

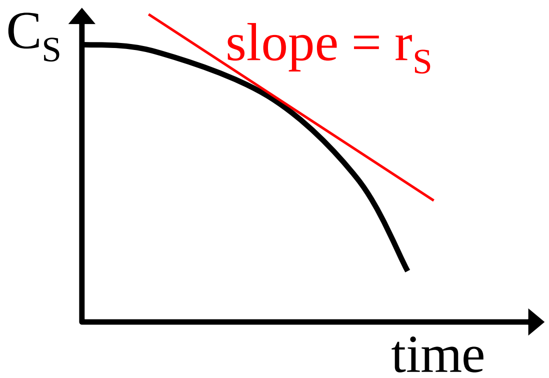
From Biochemistry
Enzymatic kinetic

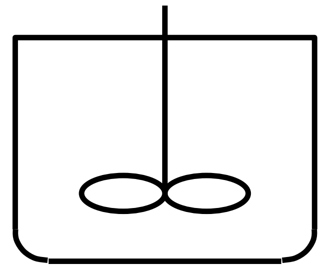
From Microbiology
Monod growth kinetic

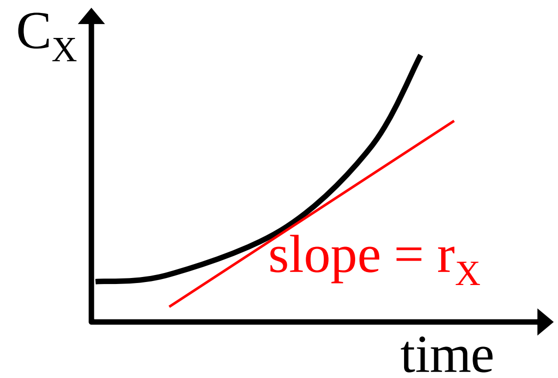
This "ratio's of rates" are linked by biomass relates yields

$$\frac{\mu}{q_S} = Y_{SX} = \frac{\text{Specific rate of biomass production } [kgX.kgX^{-1}.hr^{-1}]}{\text{Specific rate of substrate consumption } [kgS.kgX^{-1}.hr^{-1}]}$$

Quantification of r_i, q_i, Y_{ij} in BATCH reactor







Substrate rate?
Use substrate mass balance

$$\frac{d(VC_S)}{dt} = r_S V \quad \Rightarrow \quad r_S = \frac{1}{V}\frac{d(VC_S)}{dt}$$

$$\text{constant volume} \Rightarrow r_S = \frac{dC_S}{dt} = \textit{slope}$$

$$q_S = \frac{1}{C_X}\frac{dC_S}{dt}$$

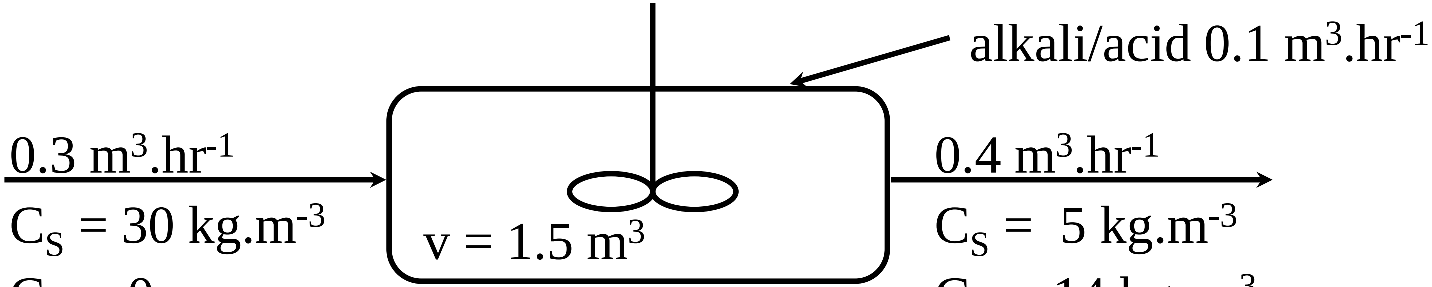
Biomass rate ?
Use the biomass mass balance

$$\frac{d(VC_X)}{dt} = r_X V \Rightarrow r_X = \frac{1}{V}\frac{d(VC_X)}{dt}$$

$$\text{constant volume} \Rightarrow r_X = \frac{dC_X}{dt} = \textit{slope}$$

$$q_X = \mu = \frac{r_X}{C_X} = \frac{1}{C_X}\frac{dC_X}{dt}$$

Quantification of r_i, q_i, Y_{ij} in CHEMOSTAT reactor



Inflow ($0.3\ m^3.hr^{-1}$):
$C_S = 30\ kg.m^{-3}$
$C_X = 0$
$C_P = 0$

Outflow ($0.4\ m^3.hr^{-1}$):
$C_S = 5\ kg.m^{-3}$
$C_X = 14\ kg.m^{-3}$
$C_P = 2\ kg.m^{-3}$

Constant volume
S.S. Steady State
Ideally **mixed**

$$Accumulation_i = \sum R_i^{IN} - \sum R_i^{OUT} + \sum R_i^{Conversions}$$

Mass Balance at Steady State
→ **No accumulation**

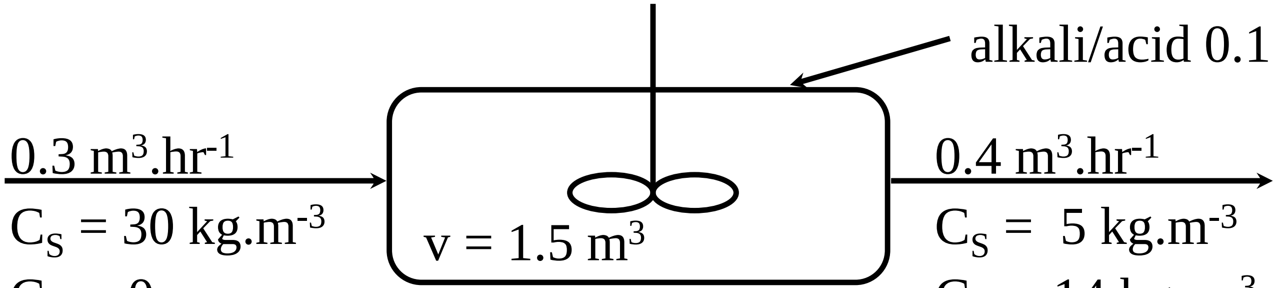
(1) Calculation of **R_i** and **r_i** rates for Biomass X, Substrate S and Product P

X: growth + in – out = 0 ; R_X = growth = - (in – out) [kg X.hr^{-1}]

S: consumption + in – out = 0 ; R_S = consumption = - (in – out) [kg S.hr^{-1}]

P: production + in – out = 0; R_P = production = - (in – out) [kg P.hr^{-1}]

Quantification of r_i, q_i, Y_{ij} in CHEMOSTAT reactor



Constant volume
S.S. Steady State
Ideally **mixed**

Mass Balance at Steady State → **No accumulation**

(1) Calculation of **R_i** and **r_i** rates for Biomass **X**

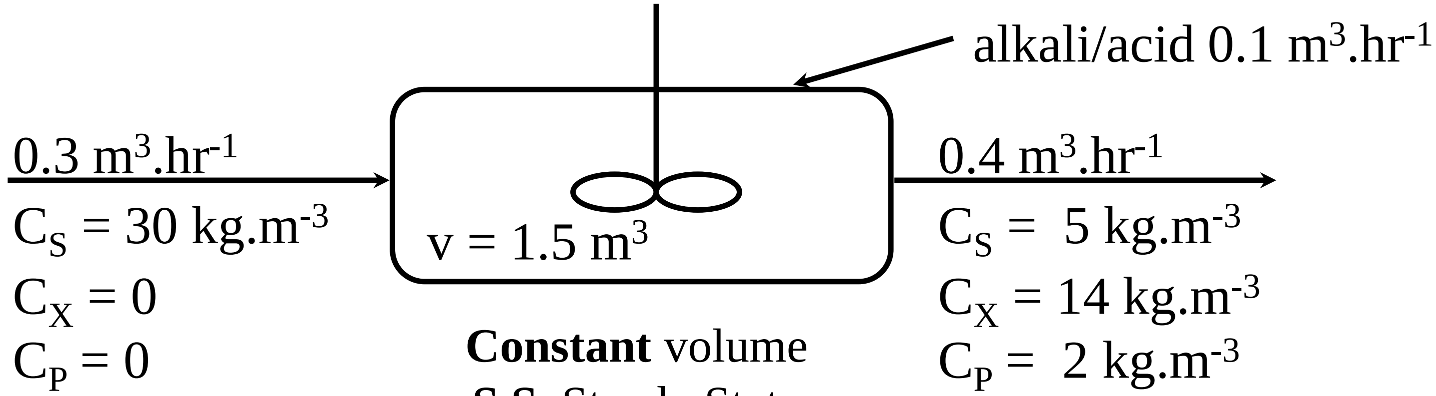
> r_i Volumetric rate = R_i / $V_{reactor}$

$$X\text{: growth + in – out} = 0 \; ; \; R_X + (0*0.3) – (14*0.4) = 0 \; [kgX.h^{-1}]$$

$$R_X = -[\, 0 - (14*0.4)] = 5.6 \; [kgX.h^{-1}]$$

$$r_X = R_X / V = (14*0.4)/1.5 = 3.73 \; [kgX.m^{-3}.h^{-1}]$$

Quantification of r_i, q_i, Y_{ij} in CHEMOSTAT reactor



Constant volume
S.S. Steady State
Ideally **mixed**

Mass Balance at Steady State → **No accumulation**

(1) Calculation of **R_i** and **r_i** rates for Substrate **S**

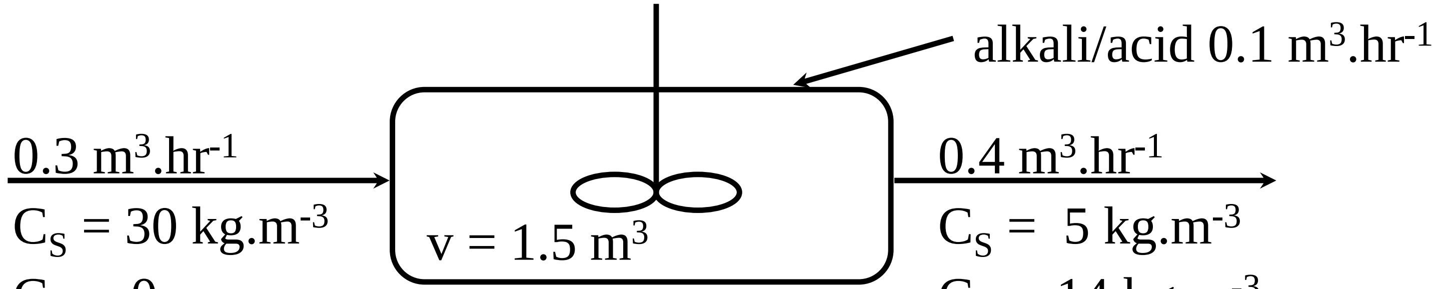
r_i Volumetric rate = R_i / $V_{reactor}$

S: consumption + in – out = 0; $R_S + (30*0.3) - (5*0.4) = 0$ [kgS.h^{-1}]

$R_S = -[(30*0.3) - (5*0.4)] = -7$ [kgS.h^{-1}]

$r_S = R_S / V = -7/1.5 = -4.66$ [kgS.m^{-3}.h^{-1}]

Quantification of r_i, q_i, Y_{ij} in CHEMOSTAT reactor



Inlet: $C_S = 30\ kg.m^{-3}$, $C_X = 0$, $C_P = 0$

Outlet: $C_S = 5\ kg.m^{-3}$, $C_X = 14\ kg.m^{-3}$, $C_P = 2\ kg.m^{-3}$

Constant volume
S.S. Steady State
Ideally **mixed**

Mass Balance at Steady State → **No accumulation**

(1) Calculation of R_i and r_i rates for Product **P**

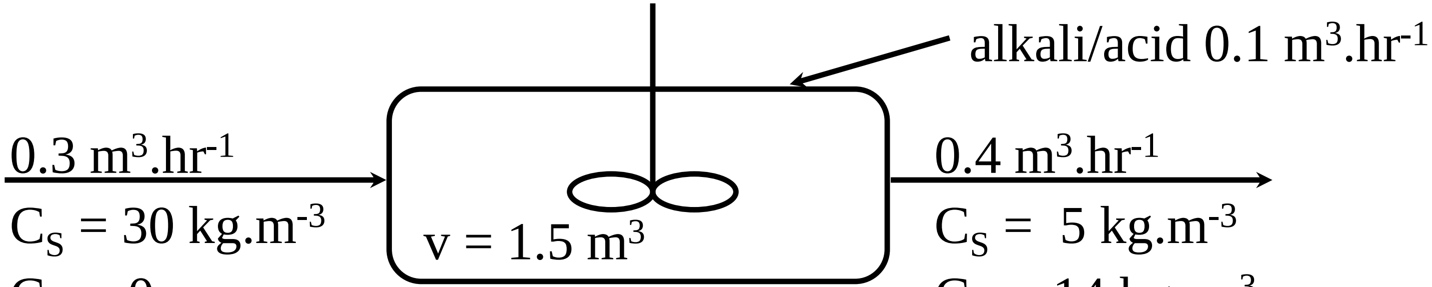
r_i Volumetric rate = $R_i / V_{reactor}$

P: production + in – out = 0; $R_P + (0*0.3) - (2*0.4) = 0$ [kgP.h^{-1}]

$R_P = -[(0*0.3) - (2*0.4)] = 0.8$ [kgP.h^{-1}]

$r_P = R_P / V = 0.8/1.5 = 0.53$ [kgP.m^{-3}.h^{-1}]

Quantification of r_i, q_i, Y_{ij} in CHEMOSTAT reactor



Constant volume
S.S. Steady State
Ideally **mixed**

(2) Calculation of q_i specific rates

r_X = 3.73 [kgX.m^{-3}.h^{-1}]
r_S = - 4.66 [kgS.m^{-3}.h^{-1}]
r_P = 0.53 kg [kgP.m^{-3}.h^{-1}]

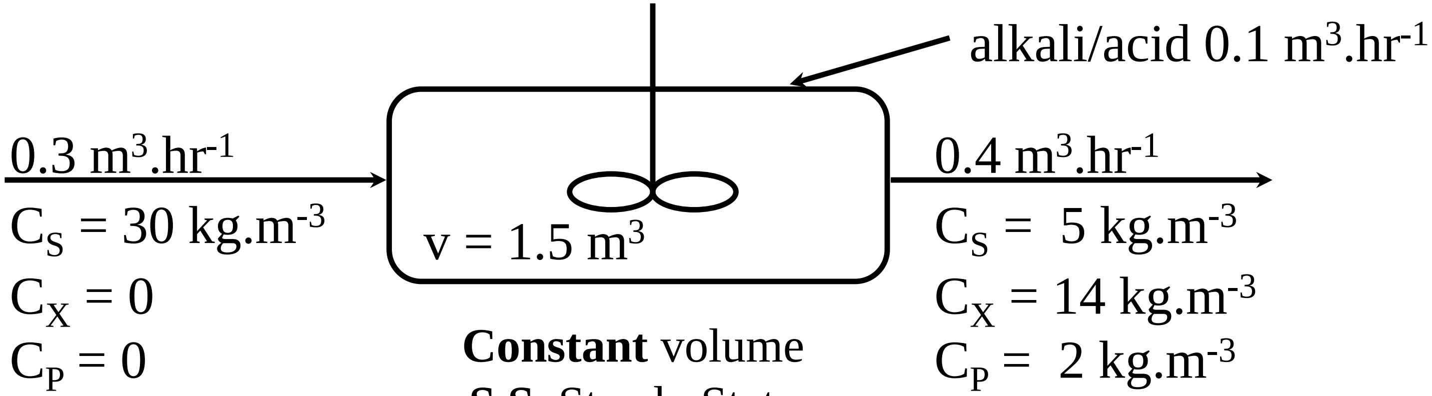
q_i Specific rate = r_i / Biomass concentration

X: $q_X = \mu = r_X/C_X = 3.73/14 = 0.26$ [kgX.m^{-3}.h^{-1}.(kgX.m^{-3})$^{-1}$] = 0.26 [h^{-1}]

S: $q_S = r_S/C_X = -4.66/14 = -0.33$ [kgS.kgX^{-1}.h^{-1}]

P: $q_P = r_P/C_X = 0.53/14 = 0.037$ [kgP.kgX^{-1}.h^{-1}]

Quantification of r_i, q_i, Y_{ij} in CHEMOSTAT reactor



Constant volume
S.S. Steady State
Ideally **mixed**

(3) Calculation of $\mathbf{Y_{ij}}$ yields

$$Y_{ij} = \left|\frac{R_j}{R_i}\right| = \left|\frac{r_j}{-r_i}\right| = \left|\frac{q_j}{q_i}\right|$$

$q_X = 0.26\ [h^{-1}]$

$q_S = -0.33\ [kgS.kgX^{-1}.h^{-1}]$

$q_P = 0.037\ [kgPS.kgX^{-1}.h^{-1}]$

$r_X = 3.73\ [kgX.m^{-3}.h^{-1}]$

$r_S = -\ 4.66\ [kgS.m^{-3}.h^{-1}]$

$r_P = 0.53$ kg $[kgP.m^{-3}.h^{-1}]$

$$Y_{SX} = |\mu/q_S| = |0.26/-0.33| = 0.8 = |r_X/r_S| = |3.73/-4.66| = 0.8\ [kgX.kgS^{-1}]$$

$$Y_{SP} = |r_P/r_S| = |0.53/-4.66| = 0.11\ [kgP.kgS^{-1}]$$

$$Y_{XP} = |r_P/r_X| = |0.53/3.73| = 0.14\ [kgP.kgX^{-1}]$$