Reactors I

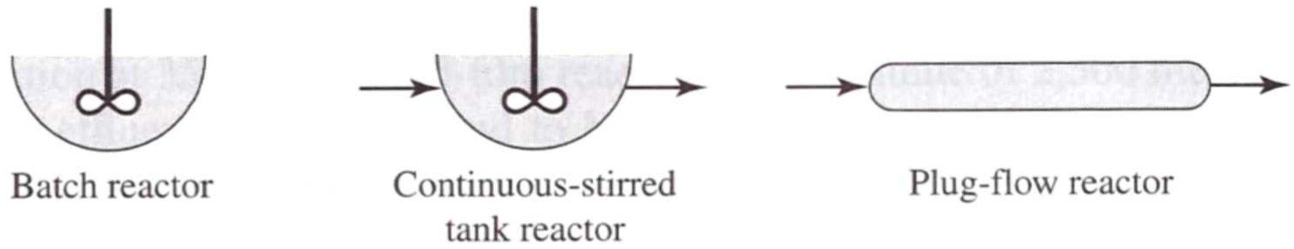
Today's class

- Types of bioreactors
- Generic approach for reactor analysis
- Reactor analysis example: batch reactor
  - Batch reactor analysis for 1st order reaction
  - Batch reactor analysis for Monod kinetics

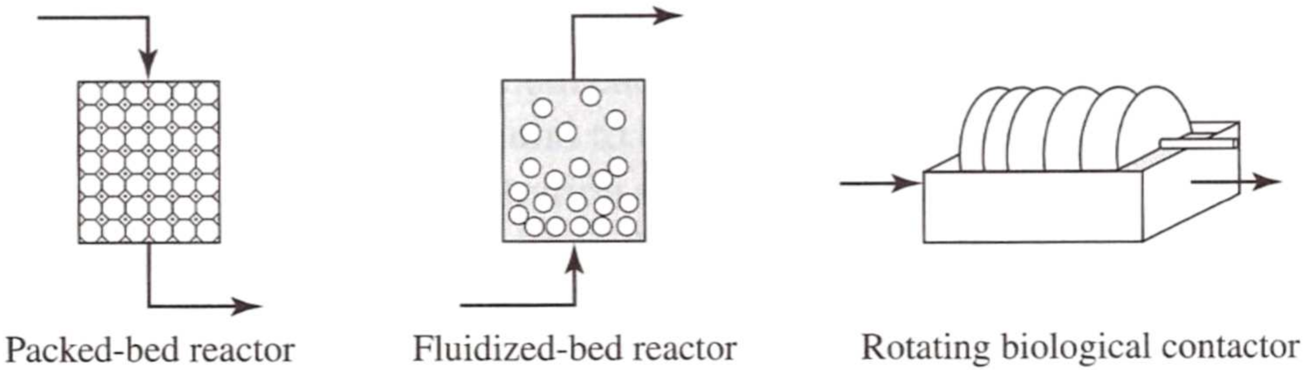
    (with some knowledge buildup for numerical analysis)

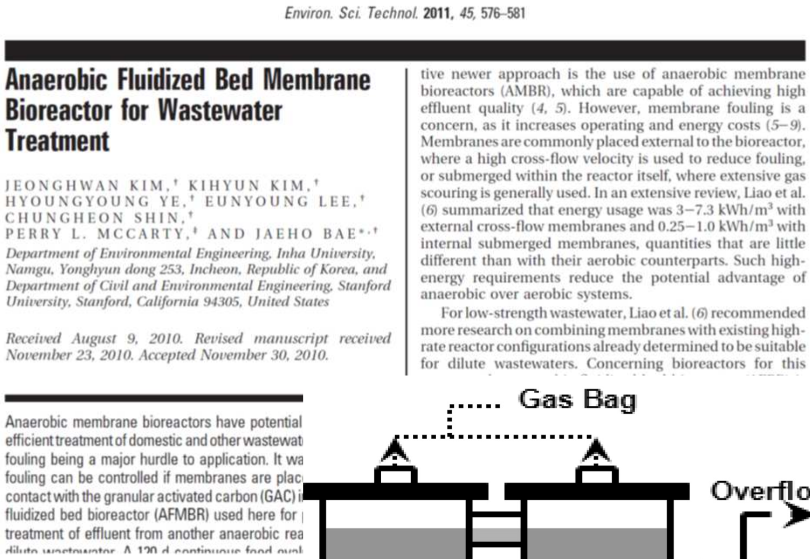
Bioreactors

Suspended growth:



Attached growth:





Environ. Sci. Technol. **2011**, *45*, 576–581

Anaerobic Fluidized Bed Membrane Bioreactor for Wastewater Treatment

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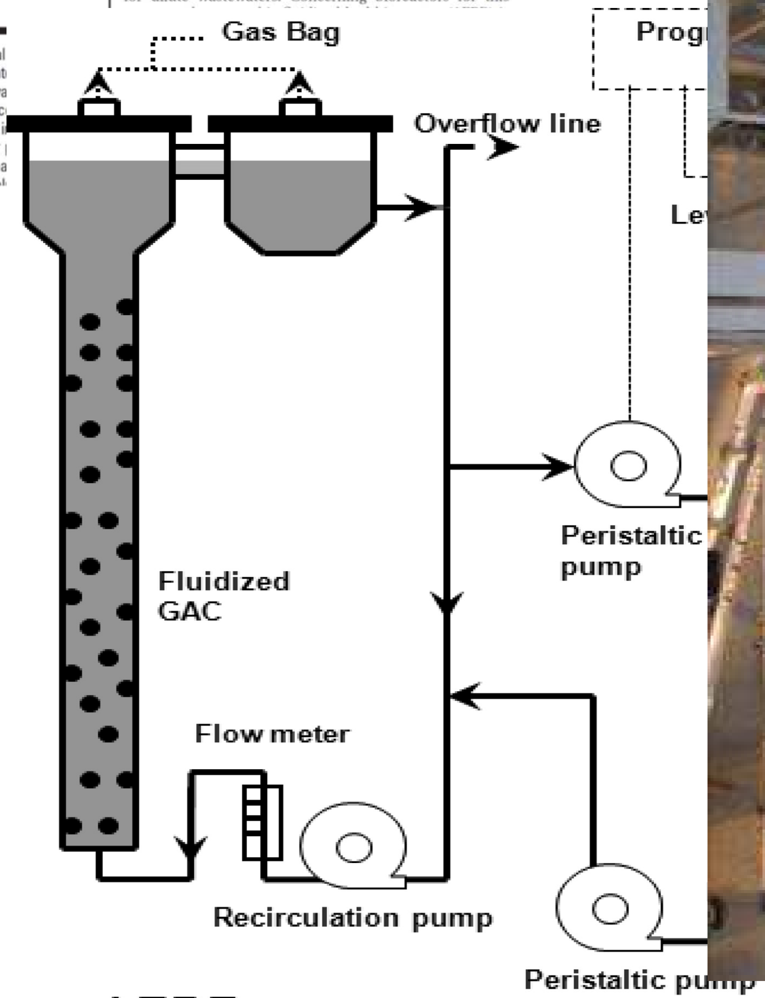
Received August 9, 2010. Revised manuscript received November 23, 2010. Accepted November 30, 2010.

Anaerobic membrane bioreactors have potential
efficient treatment of domestic and other wastewat
fouling being a major hurdle to application. It wa
fouling can be controlled if membranes are plac
contact with the granular activated carbon (GAC) i
fluidized bed bioreactor (AFMBR) used here for
treatment of effluent from another anaerobic rea

tive newer approach is the use of anaerobic membrane bioreactors (AMBR), which are capable of achieving high effluent quality (4, 5). However, membrane fouling is a concern, as it increases operating and energy costs (5–9). Membranes are commonly placed external to the bioreactor, where a high cross-flow velocity is used to reduce fouling, or submerged within the reactor itself, where extensive gas scouring is generally used. In an extensive review, Liao et al. (6) summarized that energy usage was 3–7.3 kWh/m³ with external cross-flow membranes and 0.25–1.0 kWh/m³ with internal submerged membranes, quantities that are little different than with their aerobic counterparts. Such high-energy requirements reduce the potential advantage of anaerobic over aerobic systems.

For low-strength wastewater, Liao et al. (6) recommended more research on combining membranes with existing high-rate reactor configurations already determined to be suitable for dilute wastewaters. Concerning bioreactors for this



-AFBR-

-AFMBR-

Chemical Engineering Journal 426 (2021) 131912

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Anaerobic membrane bioreactor model for design and prediction of domestic wastewater treatment process performance

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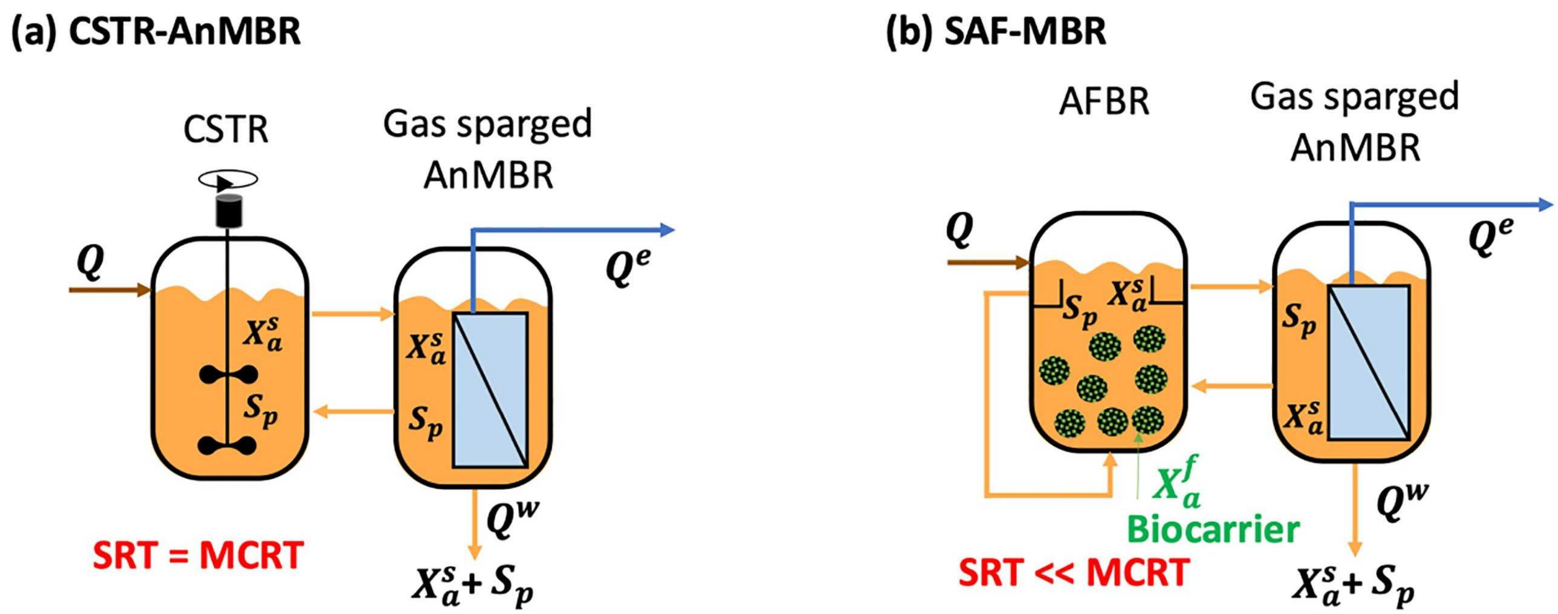
A R T I C L E I N F O

Keywords:
Anaerobic membrane bioreactor

A B S T R A C T

Anaerobic treatment of municipal wastewater that produces energy and low levels of biosolids for disposal has the potential to replace conventional aerobic processes. Here we propose a generic model for anaerobic mem-



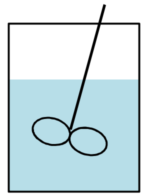
Suspended vs. attached growth

suspended growth

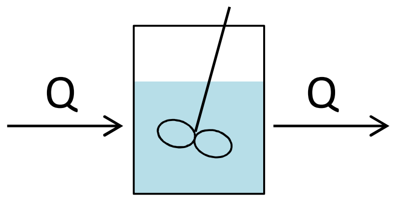
attached growth

Reactors for suspended growth

- **Batch reactor**
  - Bench-scale test systems
  - Some wastewater processes – “sequencing batch reactors”



- **Continuously-stirred tank reactor (CSTR)**
  - Activated sludge
  - Flocculator



- **Plug flow reactor (PFR)**
  - Disinfection
  - Long river/canal
  - Pipeline/aqueduct

Reactor analysis

1. Draw schematics, define control volume, make assumptions if necessary
2. Set mass balance (for a **single** substance!!!)

(mass rate of accumulation)

= (rate of mass in) – (rate of mass out)

+ (mass rate of gain/loss)

↖

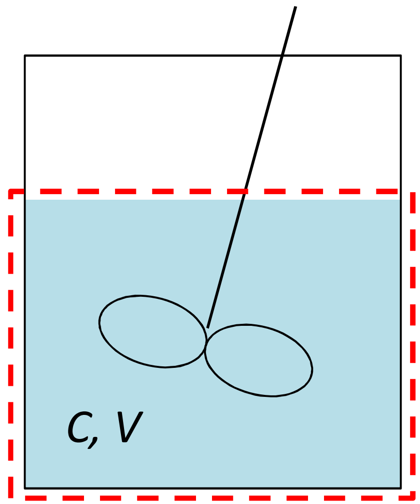
Any processes related to gain/loss, but here we are interested in reactions!

3. Rearrange/solve the equation to a useful form

Reactor analysis: Batch reactor, 1st order

1) Schematics, CV & assumption:

entire reactor as CV, complete mixing, initial concentration = C_0



2) Set mass balance (for the contaminant)

$$\frac{dC}{dt} = -kC$$

3) Rearrange/solve

$$\frac{dC}{C} = -kdt \Rightarrow \int_{C_0}^{C} \frac{dC}{C} = -\int_0^t kdt \Rightarrow \ln C - \ln C_0 = -kt$$

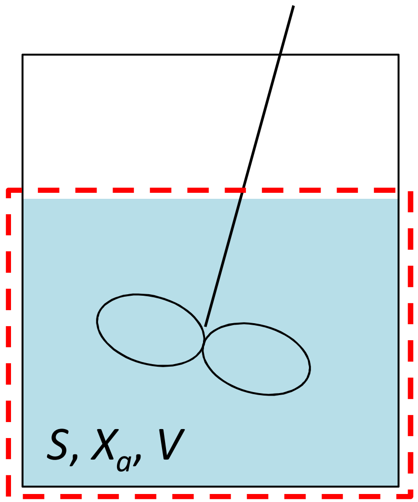
$$C/C_0 = e^{-kt}$$

Reactor analysis: Batch reactor, Monod

1) Schematics, CV & assumption:

initial substrate concentration = S^0

initial active biomass concentration = X_a^0



2) Set mass balance

(one for substrate, one for active biomass)

[substrate mass balance]

$$\frac{dS}{dt} = r_{ut} = -\frac{\hat{q}S}{K+S}X_a$$

[active biomass mass balance]

$$\frac{dX_a}{dt} = \mu X_a = \left(Y\frac{\hat{q}S}{K+S} - b\right)X_a = r_{net}$$

r_{net} = net rate of active biomass growth ($M_xL^{-3}T^{-1}$)

Batch, Monod: Governing & initial eqs.

3) Rearrange/solve

We need to get a solution for…

Governing equations

$$\frac{dS}{dt} = -\frac{\hat{q}S}{K+S}X_a$$

$$\frac{dX_a}{dt} = \left(Y\frac{\hat{q}S}{K+S} - b\right)X_a$$

Initial conditions

$$S(t=0) = S^0 \qquad X_a(t=0) = {X_a}^0$$

Batch, Monod: Challenge

Our interest would be *S* vs *t*, X_a vs *t*

The math here is much more difficult than it was for 1st order reaction because:

- There are two variables which are inter-correlated
- The differential equations are nonlinear with respect to *S*

Two ways of solving a mathematical model:

1) **Analytical solution** – an exact solution

   - such as $S = f(t)$, $X_a = g(t)$; not always available

2) **Numerical solution** – an approximate solution

Batch, Monod: Analytical solution

We need an assumption which is only occasionally acceptable that decay is negligible.

Then,

$$X_a = X_a{}^0 + Y(S^0 - S)$$ (biomass growth) = (true yield) x (substrate utilized)

The two mass balance equations are reduced to one nonlinear differential eq.:

$$\frac{dS}{dt} = -\frac{\hat{q}S}{K+S}\left[X_a{}^0 + Y(S^0 - S)\right]$$

Using the best knowledge of math, we get:

$$t = \frac{1}{\hat{q}}\left\{\left(\frac{K}{X_a{}^0 + YS^0} + \frac{1}{Y}\right) ln\left(X_a{}^0 + YS^0 - YS\right) - \left(\frac{K}{X_a{}^0 + YS^0}\right) ln\frac{SX_a{}^0}{S^0} - \frac{1}{Y} lnX_a{}^0\right\}$$

[5.11]

We fail to get an explicit solution of ***S*** as a function of ***t***

Batch, Monod: Numerical solution

$$\frac{dS}{dt} = -\frac{\hat{q}S}{K+S}X_a \qquad \frac{dX_a}{dt} = \left(Y\frac{\hat{q}S}{K+S} - b\right)X_a$$

Divide the time range into finite time steps with a length of Δt.

Then, between nth and n+1th time step, the 1st derivatives can be approximated as:

$$\frac{dS}{dt} \approx \frac{S^{n+1} - S^n}{\Delta t} \qquad \frac{dX_a}{dt} \approx \frac{{X_a}^{n+1} - {X_a}^n}{\Delta t}$$

S^n & ${X_a}^n$: S & X_a values at nth time step, respectively

If nth time step data are used for the right hand sides of the equations it is called as an "explicit" method.

cf) "implicit" method uses n+1th time step

Let's try explicit method:

$$\frac{S^{n+1} - S^n}{\Delta t} = -\frac{\hat{q} S^n}{K + S^n} {X_a}^n \quad \Rightarrow \quad S^{n+1} = \left(1 - \frac{\hat{q}}{K + S^n} {X_a}^n \Delta t\right) S^n$$

$$\frac{{X_a}^{n+1} - {X_a}^n}{\Delta t} = \left(Y \frac{\hat{q} S^n}{K + S^n} - b\right) {X_a}^n \quad \Rightarrow \quad {X_a}^{n+1} = \left\{1 + \left(Y \frac{\hat{q} S^n}{K + S^n} - b\right) \Delta t\right\} {X_a}^n$$

0th time step S^0 ${X_a}^0$

↓

1st time step S^1 ${X_a}^1$

:

nth time step S^n ${X_a}^n$

↓

n+1th time step S^{n+1} ${X_a}^{n+1}$

: