Chapter 5. Reactors

- Reactors
  - many different types exist for environmental engineering
  - generally designed to emphasize suspended growth or biofilms

- that make use of suspended growth are also called:
  - suspended-floc, dispersed-growth, slurry reactors

- that make use of biofilms are also called:
  - fixed-film, attached-growth, immobilized reactors

- Engineer must understand
  1) kinetics of substrate removal by different types of microorganisms
  2) fundamental properties of different reactor types
5. Reactors

- Factors influencing the choice among the different reactor types:
  - physical & chemical characteristics of the waste being considered
  - concentration of contaminants being treated
  - presence or absence of oxygen
  - efficiency of treatment and system reliability required
  - climatic conditions under which the reactor will operate
  - number of different biological processes involved in the overall treatment system
  - skills & experience of those who will operate the system
  - relative costs at a given location and time for construction and operation of different possible reactor configurations

- The aim of this chapter:
  i) how to construct mass balances for different reactors,
  ii) how to use of mass balances to derive basic equations that describe the relationship between reactor size and treatment performance.
5.1 Reactor Types

- Typical reactors used in environmental application

**Basic reactors**

- Batch reactor
- Continuous-stirred tank reactor
- Plug-flow reactor

**Biofilm reactors**

- Packed-bed reactor
- Fluidized-bed reactor
- Rotating biological contactor
## 5.1 Reactor Types

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Typical Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Reactors</strong></td>
<td></td>
</tr>
<tr>
<td>Batch</td>
<td>BOD test, high removal efficiency of individual wastewater constituents</td>
</tr>
<tr>
<td>Continuous-Flow</td>
<td>Anaerobic digestion of sludges and concentrated wastes, aerated lagoon</td>
</tr>
<tr>
<td>Stirred-Tank (CSTR)</td>
<td>treatment of industrial wastes, stabilization ponds for municipal and</td>
</tr>
<tr>
<td></td>
<td>industrial wastes, part of activated sludge treatment of municipal and</td>
</tr>
<tr>
<td></td>
<td>industrial wastewaters</td>
</tr>
<tr>
<td>Plug-Flow (PFR)</td>
<td>Activated sludge treatment of municipal and industrial wastes, aerated lagoon</td>
</tr>
<tr>
<td></td>
<td>treatment of industrial wastes, stabilization ponds for municipal and</td>
</tr>
<tr>
<td></td>
<td>industrial wastes, nitrification, high-efficiency removal of individual</td>
</tr>
<tr>
<td></td>
<td>wastewater constituents</td>
</tr>
<tr>
<td><strong>Biofilm Reactors</strong></td>
<td></td>
</tr>
<tr>
<td>Packed Bed</td>
<td>Aerobic and anaerobic treatment of municipal and industrial wastewaters,</td>
</tr>
<tr>
<td></td>
<td>organic removal, nitrification, denitrification</td>
</tr>
<tr>
<td>Fluidized Bed</td>
<td>Aerobic treatment of low BOD concentration wastewaters, toxic organic</td>
</tr>
<tr>
<td></td>
<td>biodegradation, anaerobic treatment, denitrification</td>
</tr>
<tr>
<td>Rotating Biological</td>
<td>Aerobic treatment of municipal and industrial wastewaters, organic removal,</td>
</tr>
<tr>
<td>Contactor (RBC)</td>
<td>nitrification</td>
</tr>
</tbody>
</table>
A) Batch reactors:

- the simplest suspended-growth reactor

- biochemical reactions take place without new additions until the reaction is complete

- commonly used in laboratory-scale

- kinetics of contaminant removal is similar to that of an ideal plug-flow reactor
Cyclic operation in a single reactor:

1) Fill, 2) React (aerobic/anoxic or anoxic/aerobic),
3) Settle, 4) Draw, 5) Idle

SBR can also employ several batch reactors operated in parallel.
5.1.1 B) Sequencing Batch Reactor (SBR)

**FIGURE 8-21**
Typical operating sequence for a sequencing batch reactor [37].
### 5.1.1 B) Sequencing Batch Reactor (SBR)

<table>
<thead>
<tr>
<th>Operational step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fill</strong></td>
<td>The purpose of the fill operation is to add substrate (raw wastewater or primary effluent) to the reactor. The fill process typically allows the liquid level in the reactor to rise from 25 percent of capacity (at the end of idle) to 100 percent. If controlled by time, the fill process normally lasts approximately 25 percent of the full cycle time.</td>
</tr>
<tr>
<td><strong>React</strong></td>
<td>The purpose of react is to complete the reactions that were initiated during fill. Typically, react takes up 35 percent of the total cycle time.</td>
</tr>
<tr>
<td><strong>Settle</strong></td>
<td>The purpose of settle is to allow solids separation to occur, providing a clarified supernatant to be discharged as effluent. In an SBR, this process is normally much more efficient than in a continuous-flow system because in the settle mode the reactor contents are completely quiescent.</td>
</tr>
<tr>
<td><strong>Draw(^b)</strong></td>
<td>The purpose of draw is to remove clarified treated water from the reactor. Many types of decant mechanisms are in current use, with the most popular being floating or adjustable weirs. The time dedicated to draw can range from 5 to 30 percent of the total cycle time (15 minutes to 2 hours), with 45 minutes being a typical draw period.</td>
</tr>
<tr>
<td><strong>Idle(^b)</strong></td>
<td>The purpose of idle in a multitank system is to provide time for one reactor to complete its fill cycle before switching to another unit. Because idle is not a necessary phase, it is sometimes omitted.</td>
</tr>
</tbody>
</table>

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\(^a\)Adapted from Ref. 37.

\(^b\)Sludge wasting usually occurs during the settle or idle phases, but wasting can occur in the other phases depending on the mode of operation.
B) Sequencing Batch Reactor (SBR)

- Advantages of SBR:

1) Total capital costs are significantly reduced due to the elimination of clarifiers and recirculation facilities.

2) Operating flexibility is greatly increased, since the cycle format can be easily modified at any time to offset i) change in process conditions, ii) influent characteristics or iii) effluent objectives.

3) Process reliability is greatly improved because the SBR process is not affected by hourly, daily, or seasonal feed variations.

4) Since only one vessel is used for all process operations, plant extension is simplified.

5) Better resistance to sludge bulking, since the biomass undergoes cyclic feast-famine conditions, which have been proven to produce better settling sludge than continuous flow.
5.1.1 C) Continuous-flow stirred-tank reactor (CSTR), or completely mixed reactor:

- used to culture organisms or to study basic biochemical phenomena in laboratory (chemostat)
- liquid or slurry stream is continuously introduced, and liquid contents are continuously removed from the reactor
- concentration of substrates and microorganisms are the same everywhere throughout the reactor (Ideal CSTR); it makes analysis of CSTR comparatively simple.
5.1.1 D) plug-flow reactor (PFR)

→ Sometimes referred to *tubular reactor* or *piston-flow reactor*.

→ In the ideal PFR, the flow moves through the reactor with no mixing with earlier or later entering flows. Hence if one knows the flow rate to the reactor and its size, the location of the element at any time can be calculated.

→ Unlike the CSTR, the concentrations of substrates and microorganisms vary throughout the reactor.

→ An ideal PFR is difficult to realize in practice, because mixing in the direction of flow is impossible to prevent.
5.1.1 Comparison of CSTR and PFR

1) The high rate of substrate utilization at the entrance of reactor in PFR because the substrate concentrations are highest at the entrance.

→ If other conditions are the same, a higher S gives a higher rate of reaction. So a PFR generally produces a higher conversion of S in a given volume than a CSTR. (advantage of PFR).

→ It exceeds the ability to supply sufficient oxygen (high DO demand at the entrance and low DO demand at the exit) in an aerobic system. Thus the aerators for PFR should be designed to provide more oxygen in the inlet region. (disadvantage of PFR)

→ It results in excess organic acid production and pH problems, e.g., destruction of methanogens at low pH in an anaerobic system. (disadvantage of PFR)
5.1.1 Comparison of CSTR and PFR

2) In CSTR, the S in the reactor is the same as S in the effluent. So the fresh feed is immediately dispersed into an environment of low S. In PFR, the S decreases along the length of reactor.

→ If no biomass enters PFR, no biological reaction would occur and the reactor washes out.

→ On the other hand, the influent to a CSTR is mixed with reactor fluid containing biomass so that a CSTR can be sustained even in the absence of biomass in the feed.

→ Processes for *in situ* biodegradation of contaminants in ground waters often operate similar to PFR. Here, mixing in the direction of flow (longitudinal) is generally small, making plug flow the natural outcome.
3) The CSTR is more stable than a PFR in response to toxic and shock loadings.

- If a concentrated pulse of a toxic substance enters a PFR, the concentration remains high as it moves along the PFR. Because of high concentration, the toxic substance may destroy an appreciable quantity of the biomass in the system and cause a long term upset in PFR performance.

- With a CSTR, the pulse of toxin is dispersed rapidly throughout the CSTR and its concentration level is reduced so that the metabolic processes of microorganisms may be only slightly affected by the diluted toxin.

- In general, a CSTR gives a more uniform effluent under varying feed conditions.
4) The CSTR and PFR are idealized models that are difficult to achieve in large scale biological reactors.

- In actual CSTR, short-circuiting of fluid and stagnant zones may occur because of incomplete mixing with the bulk of the reactor fluid.

- In PFR, aeration of the fluid causes longitudinal mixing and a distribution of residence times. Thus, long biological reactors with aeration are often better simulated by an axial dispersion model or a CSTR in series model.

- Tracer techniques are useful in establishing an appropriate hydraulic model for a biological reactor.
5.1.1 Practical Aspects of Reactor Design

- The deviation from two idealized flow patterns:
  1) Dead Zone (Stagnant zone)
  2) Channeling of fluid
  3) Short-circuiting caused by
     i) density current in plug-flow reactor
     ii) inadequate mixing in a CSTR

- This type of flow should be avoided since it always lowers the performance of the unit.

- The problems of non-ideal flow are intimately tied to those of scale-up.

- Often the uncontrolled factor differs widely between large and small units. Therefore ignoring this factor may lead to gross errors in design.
5.1.3 Reactor Arrangements

- Reactor arrangements

- Recycle of settled cells
- Recycle after settling
- Recycle before settling
- Reactors in series
- Reactors in parallel
### Reactor Arrangements

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycle</td>
<td>General aerobic and anaerobic treatment of municipal and industrial wastewaters, especially medium to low concentration BOD, organic removal, nitrification, denitrification</td>
</tr>
<tr>
<td>Series</td>
<td>BOD removal combined with nitrification or with nitrification and denitrification or combined with biological phosphorus removal, anaerobic staged treatment, stabilization pond treatment, sequential anaerobic and aerobic treatment of wastewaters such as for removal of specific toxic organic chemicals</td>
</tr>
<tr>
<td>Parallel</td>
<td>Generally used for redundancy and reliability in plant operation, especially with high overall wastewater flow rates</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Used for combined forms of treatment such as organic removal and nitrification, or organic removal, nitrification, and denitrification, or organic, nitrogen, and phosphorus removal; anaerobic treatment of industrial wastewaters</td>
</tr>
<tr>
<td><strong>Sequencing Batch</strong></td>
<td>Useful for high-efficiency removal of individual constituents such as biodegradable but hazardous organics, combined removals of organics, nitrogen, and phosphorus; combination of aerobic and anaerobic processes with same microorganisms</td>
</tr>
</tbody>
</table>
5. 1.3 Reactor Arrangements

1) Reactors in series:
- when different types of treatment are needed.
  
  *For example, organic oxidation (1st reactor) → nitrification (2nd reactor) → denitrification (3rd reactor)*
  
- To create plug-flow characteristics.

2) Reactors in parallel:
- to provide redundancy in the system so that some reactors can be out of service, while others on a parallel track remain in operation.
- when the total flow to be treated far exceeds the capacity of the largest practical units available.
- it maintains more of a completely mixed nature, compared to the more plug-flow nature of reactors in series.
5.2 Mass Balances

- Reactor design

1) Mass balance is the key to design and analysis of microbiological processes.

- It provides the critical information on what must be added to and removed from the process.
- It makes determine the amount of chemicals to satisfy the energy, nutrient, and environmental needs of the microorganisms.

For example: process for biological denitrification

\[
0.0333C_6H_5COO^- + 0.12NO_3^- + 0.02NH_4^+ + 0.12H^+ \rightarrow \\
\text{electron donor} \quad \text{elector acceptor} \quad \text{nitrogen source} \\
0.02C_5H_7O_2N + 0.06N_2 + 0.12CO_2 + 0.0133HCO_3^- + 0.1067H_2O
\]

[2.34]

0.02mole bacteria represents and is called; sludge, waste biomass, waste biosolids, excess biosolids
5.2 Mass Balances

2) System boundary; a control volume

- Figure 5.2 - Three possible control volumes

(a) Reactor influent stream Reactor effluent stream
   System influent stream
   Reactor
   Sludge recycle line
   Settling tank
   Sludge waste stream

(b) System effluent stream

(c) Control volume around settling tank

- Control volume around entire reactor system
## 5.2 A component may enter/or leave the control volume

<table>
<thead>
<tr>
<th>Fig.5.2-a</th>
<th>Component entered</th>
<th>Component left</th>
<th>Component Destroyed or formed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>By way of influent stream</td>
<td>effluent stream or sludge waste stream</td>
<td>Within the reactor system</td>
</tr>
<tr>
<td>Fig.5.2-b</td>
<td>influent stream</td>
<td>effluent stream</td>
<td>In the reactor</td>
</tr>
<tr>
<td>Fig.5.2-c</td>
<td>Reactor effluent stream</td>
<td>Settling tank effluent stream or sludge recycle line</td>
<td>In the settling tank</td>
</tr>
</tbody>
</table>
5.2 Mass Balances

3) *Reaction rates* affect the size of the treatment system.

-The mass balance is defined in terms of rates of mass change in the control volume.

-Each component must have its own mass balance

**components** : COD, TOC, biomass, oxygen, electron acceptor, nitrate, ammonium etc.

-In the development of equations useful for a reactor system, mass balances on several different components of interest and around several different control volumes sometimes are required.
**5.2 Mass Balances**

3) *Reaction rates* affect the size of the treatment system.

\[
\text{Rate of mass accumulation in control volume = rate(s) of mass in - rate(s) of mass out + rate(s) of mass generation}
\]

*Accumulation*: (total mass of the component) or 
( the reactor volume x the concentration ; \(d(VC)/dt\))

*Mass in / out*: mass crossed the control-volume boundaries

*Generation*: formation of the component of interest within the control volume
  - negative – component destroyed rather than being formed
  - endogenous respiration or predation
  - positive – bacteria cells produced through consumption
Rate of mass accumulation in control volume =
rate(s) of mass in - rate(s) of mass out + rate(s) of mass generation

This equation may take many mathematical forms, depending upon

i) the nature of control volume,

ii) the manner in which mass flows into and out of the control volume,

iii) what kind of reactions generate or destroy the component.
5.3 A Batch Reactor

- A batch reactor operated with mixing
  - the control volume consists of the entire reactor
  - uniformly distribution of components throughout the reactor
  - constant reactor liquid volume with time
  - only component concentrations changing with time.
  - The rate of mass accumulation = \( \frac{\text{Vdc}}{\text{dt}} \)

- Selection of the components
  - bacteria
  - limiting substrate – the electron donor

- Assumption
  - sufficiently high concentration of all other bacterial requirements such as electron acceptor and nutrients
  - at time=0, microorganisms’ concentration in the reactor = \( X^0 \) (mg/l), rate limiting substrate in the reactor = \( S^0 \) (mg/l)
5.1 Reactor Types

- Typical reactors used in environmental application

Basic reactors

- Batch reactor
- Continuous-stirred tank reactor
- Plug-flow reactor

Biofilm reactors

- Packed-bed reactor
- Fluidized-bed reactor
- Rotating biological contactor
5.3 A Batch Reactor

• **Mass balance for substrate**

Rate of mass accumulation in control volume =
rate of mass in - rate of mass out + rate(s) of mass generation

\[ \text{if no substrate added or removed} \]

\[ V \frac{dS}{dt} = V r_{\text{ut}} \]  

If rate of substrate utilization follows Monod kinetics

\[ r_{\text{ut}} = - \frac{\hat{q}S}{K + S} X_a \]

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

[5.3]  

[5.4]
5.3 A Batch Reactor

• Mass balance for microorganisms

Rate of mass accumulation in control volume =
rate of mass in - rate of mass out + rate(s) of mass generation
= 0 = 0

\[ V \frac{dX_a}{dt} = V(\mu X_a) \quad [5.6] \]

If the organism growth rate follows Monod kinetics,
\[ \mu = \frac{1}{X_a} \frac{dX_a}{dt} = \mu_{syn} + \mu_{dec} = \hat{\mu} \frac{S}{K+S} - b \]

\[ \frac{dX_a}{dt} = V \left( \hat{\mu} \frac{S}{K+S} - b \right) X_a \]

\[ \frac{dX_a}{dt} = \left( \hat{\mu} \frac{S}{K+S} - b \right) X_a \quad [5.7] \]
5.3 A Batch Reactor

- Initial conditions

\[ X_a(0) = X_a^0 \quad S(0) = S^0 \]  \[5.8\]

\[ \frac{dS}{dt} = -\frac{\hat{q}S}{K + S} X_a \]  \[5.4\]

\[ \frac{dX_a}{dt} = \left( \hat{\mu} \frac{S}{K + S} - b \right) X_a \]  \[5.7\]

Remark: 1) Interdependence between \( X_a \) and \( S \), both of which vary with time
2) In order to solve for \( X_a \) and \( S \) as functions of time, eq 5.4, 5.7 and 5.8 should be considered simultaneously.

3) Due to the nonlinear Monod forms, the systems of eq 5.4, 5.7 and 5.8 cannot be solved analytically. It must be done with a numerical solution.
4) If organism decay is considered to be negligible (\( b = 0 \) in eq 5.7), an analytical solution can be obtained. This is reasonable for cases of batch growth where organism decay is small while they are growing rapidly.
5.3 A Batch Reactor

**Assumption**: organism decay is negligible while the microorganisms are growing rapidly

Initial conditions

\[ X_a(0) = X^0_a \quad S(0) = S^0 \]  \hspace{1cm} \text{[5.8]}$

\[ X_a = X^0_a + Y\Delta S \quad \text{or} \quad X_a = X^0_a + Y \left( S^0 - S \right) \]  \hspace{1cm} \text{[5.9]}$

By substitution of eq 5.9 into eq 5.4

\[ \frac{dS}{dt} = -\frac{\hat{q}S}{K + S} X_a \]  \hspace{1cm} \text{[5.4]}$

\[ \frac{dS}{dt} = -\frac{\hat{q}S}{K + S} \left[ X^0_a + Y \left( S^0 - S \right) \right] \]  \hspace{1cm} \text{[5.10]}$

By integration, subject to the boundary conditions by eq 5.8

\[ t = \frac{1}{\hat{q}} \left\{ \left( \frac{K}{X^0_a + YS^0} + \frac{1}{Y} \right) \ln \left( X^0_a + YS^0 - YS \right) - \left( \frac{K}{X^0_a + YS^0} \right) \ln \frac{SX^0_a}{S^0} - \frac{1}{Y} \ln X^0_a \right\} \]  \hspace{1cm} \text{[5.11]}$
5.3 A Batch Reactor

\[ t = \frac{1}{\hat{q}} \left\{ \frac{K}{X^0_a +YS^0} + \frac{1}{Y} \ln \left( X^0_a +YS^0 -YS \right) - \frac{K}{X^0_a +YS^0} \ln \frac{SX^0_a}{S^0} - \frac{1}{Y} \ln X^0_a \right\} \]  \hspace{1cm} [5.11]

\[ X_a = X^0_a + Y \left( S^0 - S \right) \]  \hspace{1cm} [5.9]

- When t is known, S can be solved by eq 5.11.
  And also \( X_a \) can be solved by eq 5.9.
5.3 A Batch Reactor

\( X_a^0 \) affecting bacterial growth and the substrate concentration

- The higher the initial concentration of biomass, the lower the substrate utilization time.
- For the lowest initial organism concentration, a lag period occurs before the onset of significant substrate utilization.

The increase of biomass between \( t=0 \) and \( t = t \) at \( S=0 \) is the same in all cases

\[
( = ( X_a - X_a^0 ) = Y S^0 = 0.6 \times 100 = 60 \text{ mg/L} )
\]

\[
X_a = X_a^0 + Y(S^0 - S) = X_a^0 + 0.6(100 - 0) \quad [5.9]
\]