CHAPTER III

THE ACTIVATED SLUDGE PROCESS

The most versatile of the biological treatment processes is the activated sludge process which was developed in 1963 in England (McKinney, 1962). Several types of activated sludge processes are in use today. Although varying in detail, fundamentally they are all similar.

Process Fundamental

Activated sludge process is an aerobic process that utilizes a culture in which bacterial cells are agglomerated together in "flocs". The term "activated" stems from a unique property of activated sludge. The surfaces of the flocs are highly active in adsorbing colloidal and suspended materials from solution. The activated sludge treatment of sewage involves biological oxidation of a heterogeneous continuously changing mixture of organic compounds. It can be said that the activated sludge process utilizes a culture of microorganisms to metabolize the organic and inorganic substances in wastewater. The oxidation of organic substrates in the activated sludge is accompanied by the development of a large population of microorganisms taking part in oxidation. The biochemical reaction which occurs during oxidation of organic materials by bacteria may be expressed stoichiometrically as : Inert Matter + Organic Matter + O_2 + Nutrients + Bacteria ——— ——————→ New Bacteria + CO_2 + H_2O + Additional Inert Matter.

The environmental conditions which include pH, temperature, dissolved oxygen and absence of toxic materials, must be maintained during the operation of the process.

Microorganisms

Activated sludge consists of a flocculent assemblage of microorganisms, nonliving organic matters, and inorganic meterials. The microorganisms including bacteria, fungi, protozoa and metazoa, such as rotifers, insect larvae and sometimes nematodes, are related to each other in a food chain. Bacteria and fungi decompose complex organic compounds to produce, through growth, cellular material on which protozoa feed. The protozoa, in turn, are consumed by metazoa. The latter may also feed directly upon the decomposers.

Bacteria are the Basic Group of the important microorganisms of the activated sludge process. Bacteria are single - cell protists. Their usual mode of reproduction is by binary fission, although some species reproduce sexually or by budding. They are the ones which are responsible for the stabilization of the organic matter and floc formation. Zooglea ramigera, a rod - shaped bacterium, is common in activated sludge and produces copious amounts of extracellular slime. (Mitchell, 1974). This slime is assumed to be the binding agent in the floc formation. It has been suggested that Zooglea ramigera is the most important organism in bacterial flocculation. Bacteria used soluble food and, in general, will be found wherever moisture and a food source are available. Temperature and pH play a vital role in the life and death of bacteria. The optimum pH and temperature for

growth lies between 6.5 to 7.5 and 30^{o}C, respectively.

Fungi are usually not desirable in activated sludge but are found under certain conditions. Fungi are similar to bacteria. In fact, to be technical, the bacteria are actually fungi, fission fungi. Fungi are usually classed by their mode reproduction. They reproduce sexually or asexually, by fission, budding, or spore formation. Most of the fungi tend to form filament which prevent good floc formation Very little work has been done on identification of the fungi found in activated sludge. Highly carbohydrate waste, unusuals organic compounds, low pH, and nutritional deficiencies all stimulate the growth of fungi. Fungi also have a low nitrogen requirement and need approximately one-half as much as bacteria. The optimum pH for most species is 5.6 while the range is between 2 to 9.

The protozoa do not contribute directly to the stabilization of the organic matters in the wastes being treated by the activated sludge process. The organic concentration is too low to support animal growth. But the protozoa can live off the bacteria which are utilizing organic matters. The protozoa are a group of generally motile, single-celled organisms that do not have a cell wall and reproduce by binary fission. The majority of protozoa are aerobic heterotrophs, although a few an anaerobic. Protozoa are generally an order of magnitude larger than bacteria and often consume bacteria as an energy source. The ciliata will be the primary protozoa of importance in the activated sludge process. The Free-swimming bacteria protozoa will predominate with a high free-swimming bacteria population. As the bacterial population is reduced, the free-swimming ciliates give

way to the stalked ciliates. The lower feed level cannot support the high energy-demanding, free-swimming ciliates.

The rotifer is the simplest of the multicell animals. The rotifer is an aerobic, heterotrophic, and multicellular animal. It name is derived from the fact that it has two sets of rotating cilia on it head which are used for motility and capturing food. Rotifers are not often seen in activated sludge processes. It has only been with the advent of the complete oxidation type activated sludge systems that the rotifers have been seen as the predominant animal form. Their presence is indicative of an effluent that is low in organic matter and high in dissolved oxygen. The rotifers can utilize larger fragments of activated sludge floc than can the protozoa and survive after all the free-swimming bacteria have been eaten by protozoa.

Process Description

The activated sludge process can be best described as a completely mixed continuous flow process with cellular recycle which allows a greater microorganism residence time than the hydraulic residence time. The activated sludge process consists of an aeration tank, a sedimentation tank and a recycle system for the settled sludge. Figure 3 illustrates the continuous flow stirred tank reactor (CFSTR) with cellular recycle. Organic waste is introduced into a reactor where an aerobic bacterial culture is maintained in suspension. The aerobic environment in the reactor is achieved by the use of diffused or mechanical aeration, which also serves to maintain the mixed liquor suspended solids in a completely mixed regime. The microorganisms aerobically stabilize the organic matter in the aeration tank and flow

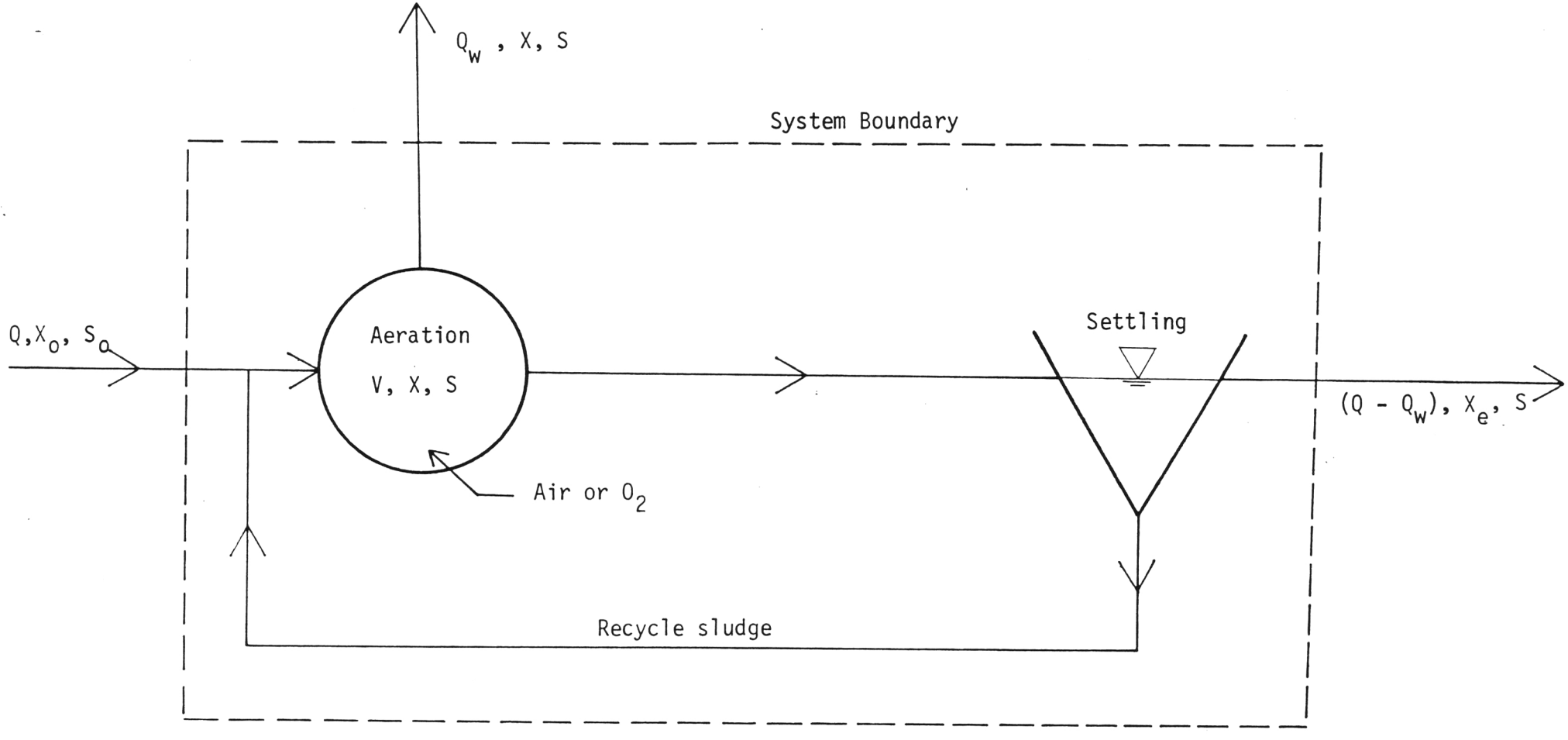

Figure 3. Schematic Diagram of Completely Mixed Activated Sludge Process with Cellular Recycle.

into a sedimentation tank. Sedimentation allows the activated sludge to flocculate and to settled out, producing a clear effluent of low organic content. A portion of the settled cells is recycled to the aeration tank to maintain the desired concentration of microorganisms in the reactor.

Because the culture is made up of organisms grown at the expense of the incoming organic materials, some method of wasting must be provided. Some cells are lost in the process effluent, but this method of wasting is undesirable as the objective of the process is to produce a low carbon, low suspended solids effluent. The best method of wasting is directly from the aeration tank or sludge recycle line. The amount of wasting necessary depends on the characteristics of the incoming wastewater and the mode of process operation.

Microbial Growth Kinetics

For a continuous flow reactor microbial growth has been shown to be expressed mathematically as :

$$R_g = -Y_{max}R_{su} - k_dX \qquad (1)$$

where R_g = net growth rate of microorganisms, mass/volume-time

Y_{max} = maximum microorgnaism cell yield coefficient, mass/mass

R_{su} = rate of substrate utilization, mass/volume-time

k_d = endogenous respiration coefficient or maintainance energy coefficient, $time^{-1}$, and

X = concentration of microorganisms, mass/volume.

This equation has been used to describe microbial growth in biological wastewater treatment processes. The rate of substrate

utilization, R_{su}, is a negative term. In a batch biological reactor where the microorganisms grow in the presence of excess substrate, the growth of microorganisms is in the exponential phase the maintainance energy requirement is very small and may be neglected. For maximum logarithmic growth equation (1) becomes :

$$R_g = -Y_{max}R_{su} \tag{2}$$

Thus, the maximum microorganism cell yield coefficient can be defined as

$$Y_{max} = -\frac{R_g}{R_{su}} \tag{3}$$

Kinetics of the Activated Sludge Process

The activated sludge process can be modelled as a completely mixed reactor with cellular recycle. A schematic diagram of the process is shown in Figure 3. Kinetic models for this process can be developed based on materials balance equations written around a system boundary.

An operating parameter, mean cell residence time, θ_c is related to the microbial growth rate, R_g, for the system and is defined as

$$\theta_c = \frac{VX}{Q_wX + (Q - Q_w)X_e} \tag{4}$$

in which

θ_c = mean cell residence time, time

V = volume of total reactor, volume

Q_w = wasted sludge volumetrio flow rate, volume/time

Q = influent volumetric flow rate, volume/time

X = microorganism concentration in total biological reactor, mass/volume

X_e = microorganism concentration in the effluent, mass/volume.

Mean cell residence time, θ_c can be used as the basis for comparing process parameters under different operating conditions.

A mass balance equation written to describe microbial growth for the system shown in Figure 3 is as follows :

[Rate of change of microorganism concentration in reactor] = [Rate of microorganism inflow to reactor] + [Net rate of microorganism growth in the reactor] - [Rate of microorganism outflow from reactor]

$$V\left(\frac{dX}{dt}\right) = QX_o + (-Y_{max}R_{su} - k_dX)V - Q_wX + (Q - Q_w)X_e \qquad (5)$$

Assuming microorganisms are absent in the influent wastewater ($X_o = 0$) and steady state conditions prevail ($\frac{dX}{dt} = 0$), equation (5) can be rearranged to yield :

$$\frac{1}{\theta_c} = -Y_{max}\frac{R_{su}}{X} - k_d \qquad (6)$$

The term $(-\frac{R_{su}}{X})$ is the specific utilization rate, U, which can be defined as :

$$U = \frac{S_o - S}{\theta X} \qquad (7)$$

in which U = specific utilization rate, $time^{-1}$

θ = hydraulic residence time, time

= volume of total reactor/influent volumetric flow rate.

Substituting equation (7) into equation (6) yields

$$\frac{1}{\theta_c} = Y_{max}U - k_d \qquad (8)$$

By plotting $1/\theta_c$ versus U, a straight line graph is obtained. From the slope and intercept of this graph, values for Y_{max} and k_d can be calculated.

For continuous culture growth (Sherrard,1976) proposed an alternate approach toward analysing the net microbial growth rate by including the effects of endogenous respirating into a variable microorganism cell yield coefficient. This cell yield coefficient is termed the observed yield, Y_{obs}, the varies with mean cell residence time, θ_c. The net microbial growth rate can be expressed in terms of Y_{obs} as follows :

$$R_g = -Y_{obs}R_{su} \qquad (9)$$

where

Y_{obs} = observed yield, mass/mass.

Rearranging equation (9), the following equation is obtained :

$$Y_{obs} = -\frac{R_g}{R_{su}} \qquad (10)$$

By substituting equation (10) into equation (8) and rearranging, the following relationship is obtained :

$$Y_{obs} = \frac{Y_{max}}{1+k_d\theta_c} \qquad (11)$$

Rearrangement of this relationship yields

$$\frac{1}{Y_{obs}} = \frac{1}{Y_{max}} + \frac{k_d\theta_c}{Y_{max}} \qquad (12)$$

By plotting $1/Y_{obs}$ versus θ_c on an arithmetic graph paper, value of k_d/Y_{max} and $1/Y_{max}$ can be obtained from the slope and intercept, respecitively. Thereby the value of Y_{max} and k_d can also be calculated.

Waste sludge production may be obtained from the expression

$$P_x = \frac{Y_{max}Q(S_o - S)}{1 + k_d\theta_c} \quad (13)$$

$$= \frac{VX}{\theta_c} \quad (14)$$

where P_x = waste sludge production, mg/day.

For the activated sludge receiving wastewater containing the reactant, i.e., heavy metal, nitrogen, organic material, etc. a general mass balance equation written to describe a reactant for the system previously shown in Figure 3 is as follows :

$$\begin{bmatrix}\text{Mass of}\\ \text{reactant}\\ \text{inflow to}\\ \text{reactor}\end{bmatrix} + \begin{bmatrix}\text{Mass of}\\ \text{reactant}\\ \text{converted in}\\ \text{the reactor}\end{bmatrix} = \begin{bmatrix}\text{Mass of}\\ \text{reactant}\\ \text{outflow from}\\ \text{reactor}\end{bmatrix} + \begin{bmatrix}\text{Accumulation}\\ \text{of reactant}\\ \text{in the}\\ \text{reactor}\end{bmatrix}$$

$$QC_o + VR_c = (Q - Q_w)C_e + Q_wC_w + V(\frac{dC}{dt}) \quad (15)$$

where

C_o = reactant concentration in the influent, mass/volume

C_w = reactant concentration in the wasting line, mass/volume

C_e = reactant concentration in the effluent, mass/volume

R_c = rate of reactant convertion, mass/volume-time.

At steady state conditions there can be no accumulation of mass of reactant in the reactor, i.e., $dC/dt = 0$.

Rearranging of equation (15) yields

$$VR_c = (Q - Q_w)C_e + Q_wC_w - QC_o \qquad (16)$$

Equation (16) can be used as a basis to describe a change in concentration of heavy metals, nitrogen concentration or substrate concentration as they pass through the activated sludge process.

Nitrification in Activated Sludge Process

When nitrogen-containing organic materials are oxidized in a biological wastewater process, ammonia-valence nitrogen is released into solution. This nitrogen is available as a nitrogen and energy source for the nitrifying bacteria. Under proper environmental conditions the activated sludge process is capable of supporting nitrifying bacteria, Nitrosomonas and Nitrobactor, which have the ability to convert ammonia to nitrates. Nitrosomonas and Nitrobactor are Gram-negative nonsporeforming rods that are highly aerobic (Mitchell, 1974). They are both obligately chemoautotrophic, differing only in the ability of Nitrosomonas to utilize NH_3 as an energy source, while Nitrobactor utilize NO_2^-.

Nitrogen in the form of the ammonium ion converted to nitrate occurs in two steps. In step one, Nitrosomonas covert ammonia to nitrite according to the equation (17). In step two, Nitrobactor take the nitrite and oxidize them to nitrate according to the equation (18).

$$NH_4^+ + \frac{3}{2}O_2 \xrightarrow{\text{Nitrosomonas}} NO_2^- + 2H^+ + H_2O \qquad (17)$$

$$NO_2^- + \frac{1}{2} O_2 \xrightarrow{\text{Nitrobactor}} NO_3^- \qquad (18)$$

The overall energy reaction for nitrification can be written as follows:

$$NH_4^+ + 2\ O_2 \xrightarrow{\text{Nitrifying bacteria}} NO_3^- + 2H^+ + H_2O \qquad (19)$$

The stoichiometric equation for nitrification expressed by equation (19) implies that the biological oxidation of 1 mg/l of NH_3-N to NO_3-N will destroy 7.14 mg/l of alkalinity as $CaCO_3$ and that 4.57 mg/l of oxygen is required.

The nitrifying bacteria are highly sensitive to the environmental conditions as follows :

1. They are stricly aerobic and require high level of oxygen.
2. Nitrobactor is inhibited at pH values above 9.5 in the presence of NH_4^+. This leads to accumulation of toxic nitrites under alkaline conditions. Nitrosomonas is active under alkaline conditions but is inhibited at pH values below 6.0.
3. The temperature optimum for nitrification is 30^oC. No activity is detected below 5^oC or above 40^oC.

The effects of environmental conditions such as dissolved oxygen, temperature, pH and concentration of inhibitor can be predicted from their effects on the growth rate of nitrifying bacteria.