



PDHonline Course C393 (1 PDH)

Fundamentals of Membrane Bioreactors

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COURSE CONTENT

1. INTRODUCTION

This course provides anyone who takes it with familiarity of wastewater and sludge treatment process. The course covers details of nitrification and denitrification processes and parameters that affect quality of treatment process such as Biological Oxygen Demand, pH and turbidity and their measurements.

2. PROCESS OVERVIEW

Sewage is created by residences, institutions, hospitals and commercial and industrial establishments. Raw influent (sewage) includes household waste liquid from toilets, baths, showers, kitchens, sinks, and so forth that is disposed of via sewers. In many areas, sewage also includes liquid industrial and commercial waste.

2.1 Objective of sewage treatment

The objective of sewage treatment is to produce a disposable effluent without causing harm or trouble to the communities and prevent pollution. Sewage treatment, or domestic wastewater treatment, is the process of removing contaminants from wastewater and household sewage effluents. It includes processes to remove physical, chemical and biological contaminants. Its objective is to produce a waste stream or treated effluent and a solid waste or sludge suitable for reuse or discharge back into the environment. This material is often inadvertently contaminated with many toxic organic and inorganic compounds. A lot of sewage also includes some surface water from roofs or hard-standing areas. The variability in runoff flow also leads to often larger than necessary, and subsequently more expensive, treatment facilities. It is preferable to have a separate system for stormwater treatment and discharge. Some jurisdictions require stormwater to receive some level of treatment before being discharged directly into waterways. Examples of treatment processes used for stormwater include sedimentation basins, wetlands, buried concrete vaults with various kinds of filters, and vortex separators to remove coarse solids.

2.2 Sewage treatment process overview

Conventional sewage treatment involves three stages, called *primary*, *secondary* and *tertiary treatment*. First, the solids are separated from the wastewater stream. Then dissolved biological matter is progressively converted into a solid mass by using indigenous, water-borne micro-organisms. Finally, the biological solids are neutralized then disposed of or re-used, and the treated water may be disinfected chemically or physically (for example by lagoons and microfiltration). The final effluent can be discharged into a stream, river, bay, lagoon or wetland, or it can be used for the irrigation of a golf course, green way or park. If it is sufficiently clean, it can also be used for groundwater recharge or agricultural purposes.

The sludges accumulated in a wastewater treatment process must be treated and disposed of in a safe and effective manner. Treatment is a process of digestion is to reduce the amount of organic matter and the number of disease-causing microorganisms present in the solids. Choice of a wastewater solid treatment method depends on the amount of solids generated and other site-specific conditions. However, in general, composting is most often applied to smaller-scale applications followed by aerobic digestion and then lastly anaerobic digestion for the larger-scale municipal applications. The most common treatment options are

- ***anaerobic digestion***,
- ***aerobic digestion***,
- ***composting***.

Anaerobic digestion is a bacterial process that is carried out in the absence of oxygen. The process can either be *thermophilic* digestion, in which sludge is fermented in tanks at a temperature of 55°C, or *mesophilic*, at a temperature of around 36°C. Though allowing shorter retention time (and thus smaller tanks), thermophilic digestion is more expensive in terms of energy consumption for heating the sludge. One major feature of anaerobic digestion is the production of biogas, which can be used in generators for electricity production and/or in boilers for heating purposes.

Aerobic digestion is a bacterial process occurring in the presence of oxygen. Under aerobic conditions, bacteria rapidly consume organic matter and convert it into carbon dioxide. The operating costs are characteristically much greater for aerobic digestion because of the energy costs needed to add oxygen to the process.

Composting is also an aerobic process that involves mixing the sludge with sources of carbon such as sawdust, straw or wood chips. In the presence of oxygen, bacteria digest both the wastewater solids and the added carbon source and, in doing so, produce a large amount of heat.

When a liquid sludge is produced, further treatment may be required to make it suitable for final disposal. Typically, sludges are thickened (dewatered) to reduce the volumes transported off-site for disposal. There is no process which completely eliminates the need to dispose of biosolids. There is, however, an additional step some cities are taking to superheat the wastewater sludge and convert it into small pelletized granules that are high in nitrogen and other organic materials. In New York City, for example, several sewage treatment plants have dewatering facilities that use large centrifuges along with the addition of chemicals such as polymer to further remove liquid from the sludge. The removed fluid, called centrate, is typically reintroduced into the wastewater process. The product which is left is called "cake" and that is picked up by companies which turn it into fertilizer pellets. This product is then sold to local farmers and turf farms as a soil amendment or fertilizer, reducing the amount of space required to dispose of sludge in landfills.

2.2 Activated Sludge treatment process overview

Secondary treatment is designed to substantially degrade the biological content of the sewage such as are derived from human waste, food waste, soaps and detergent. The majority of wastewater plants treat the settled sewage liquor using aerobic biological processes. For this to be effective, the bacteria require both oxygen and a substrate on which to live. There are a number of ways in which this is done. In all these methods, the bacteria consume biodegradable soluble organic contaminants (e.g. sugars, fats, organic short-chain carbon molecules, etc.) and bind much of the less soluble fractions into floc. Secondary treatment systems are classified as

- *fixed-film*
- *suspended-growth*.

Fixed-film treatment process including trickling filter and rotating biological contactors where the biomass grows on media and the sewage passes over its surface.

In suspended-growth systems, such as activated sludge system, the biomass is well mixed with the sewage and can be operated in a smaller space than fixed-film systems that treat the same amount of water. However, fixed-film systems are more able to cope with drastic changes in the amount of biological material and can provide higher removal rates for organic material and suspended solids than suspended growth systems.

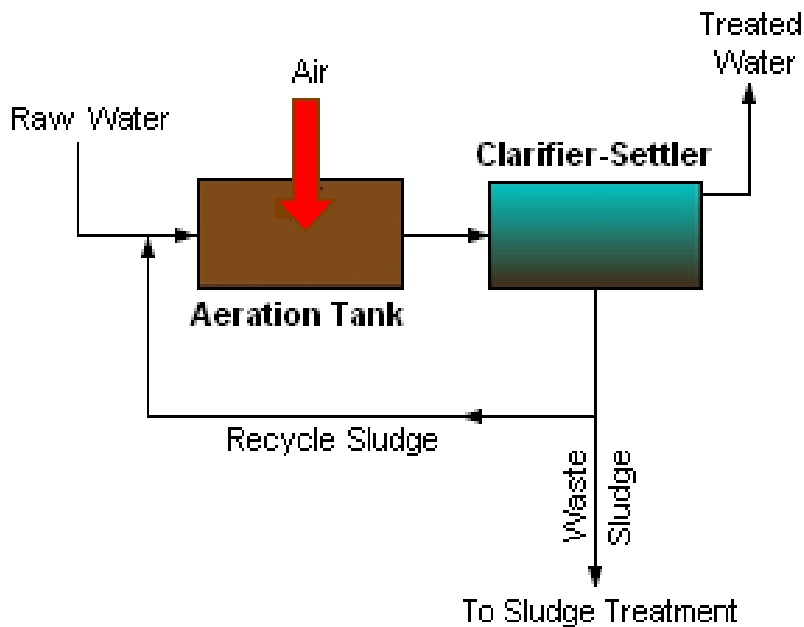


Figure 1. Activated Sludge Wastewater Treatment process diagram

Activated sludge plants encompass a variety of mechanisms and processes that use dissolved oxygen to promote the growth of biological floc that substantially removes organic material. The process traps particulate material and converts ammonia to nitrite and nitrate and ultimately to nitrogen gas, (see also nitrification and denitrification). This process uses dissolved oxygen to promote the growth of biological floc that substantially removes organic matter. The process converts ammonia to nitrite and nitrate and at the final stage to the nitrogen. At the same time particulate material is trapped in membrane microfilter. Typical Activated sludge wastewater treatment plant consists of the following components:

- ***Trash trap***
- ***Anoxic tank***
- ***Aeration tank***
- ***Membrane Filtration tank***

- *Sludge Holding tank*
- *Ancillary equipment*

As name implies, trash trap is a tank in which solid inorganic matter such as paper products, cans, sand and grits, etc. are removed from the influent by settling. Periodically, the settled trash is removed and disposed. The wastewater flows into anoxic tank either by gravity or by use of transfer pump into the anoxic tank.

In the Anoxic tank, denitrifying bacteria reduce nitrites and nitrates in the mixed liquor into nitrogen. In order to increase process efficiency, the content of the anoxic tank is being mixed constantly using either coarse bubble air diffuser or electrically driven propeller mixers.

From the anoxic tank wastewater flows into Aeration tank for further biological treatment. Aerobic digestion is accomplished by injecting air into process fluid through fine bubble air diffusers. In Aeration tank the wastewater undergoes nitrification and further denitrification.

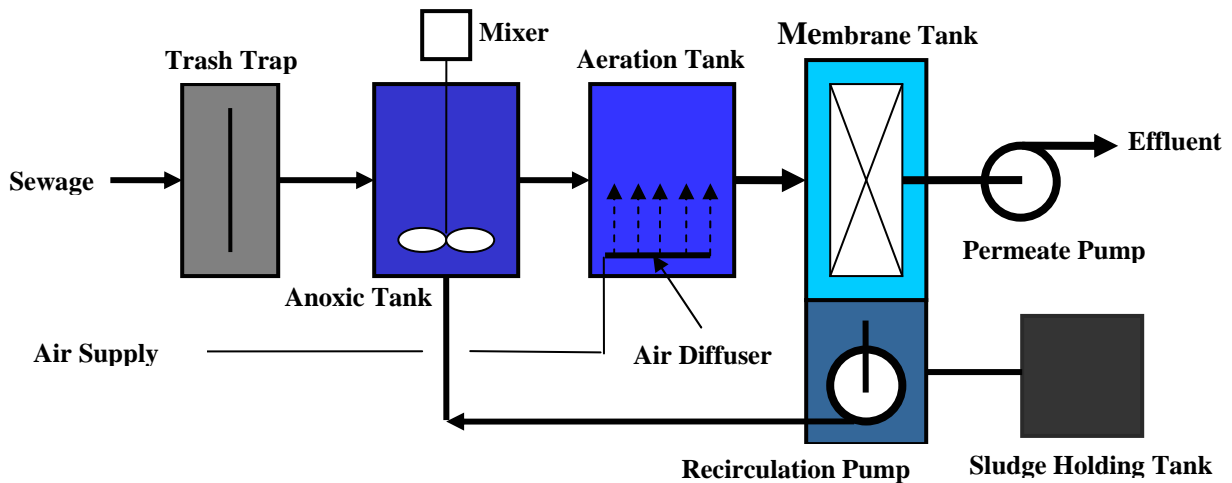


Figure 2. Membrane Bioreactor process diagram

From Aeration tank wastewater flows into Membrane Filtration tank where separation of biosolids from effluent is taking place. Separation is accomplished by pumping effluent through microfilter membranes to further treatment and discharge. An internal recirculation loop is provided between the membrane filtration tank and the anoxic tank. This recirculation loop allows mixed liquor rich in nitrates and nitrites to be partially returned to the anoxic tank for further denitrification. In order to insure high efficiency of filtration process, membranes

are continuously cleaned by an air scour system to remove solid that accumulates on the surface of the membrane filters.

After completing disinfection process, effluent is being discharged from wastewater treatment system to be used for irrigation or to be discharged to wetland. Sludge is collected in Sludge Holding tank to be disposed using methods described earlier.

3. ANCILLARY EQUIPMENT.

Wastewater Treatment Plant consists of the following ancillary equipment:

- *Chemical feed system*
- *Disinfection system*

Typically, there are three chemical feed systems:

- a. Supplemental carbon feed system that supplies methanol or sucrose that serves as a nutrient for denitrifying bacteria in the Anoxic Tank.
- b. Control of pH level in the Aeration Tank provided by metering pump that feeds caustic soda (NaOH) directly to Aeration Tank.
- c. A cleaning solution is periodically injected by metering pump into the Membrane Filtration tank.

Before effluent is discharged, it undergoes a disinfection process. Purpose of disinfection is to reduce number microorganisms in water before being discharged back to environment.

There are three main methods of the effluent disinfection

- *Chlorination*
- *UV irradiation*
- *Ozonation*

Chlorination is the most commonly used method of disinfection in the United States. Chlorination process involves feeding Sodium Hypochlorite (NaOCl) into effluent using metering pump. The main advantage of the process is that chlorination is effective and inexpensive process of removal harmful microorganisms from discharged water. Main disadvantage is that chlorination of residual organic material can generate chlorinated-organic compounds that may be carcinogenic or harmful to the environment. Residual chlorine or *chloramines*

may also be capable of chlorinating organic material in the natural aquatic environment. Further, because residual chlorine is toxic to aquatic species, the treated effluent sometimes must also be chemically dechlorinated, adding to the complexity and cost of treatment.

Ultraviolet (UV) irradiation can be used instead of chlorine, iodine, or other chemicals. Because no chemicals are used, the treated water has no adverse effect on organisms that later consume it, as may be the case with other methods. UV radiation causes damage to the genetic structure of bacteria, viruses, and other pathogens, making them incapable of reproduction. The key disadvantages of UV disinfection are the need for frequent lamp maintenance and replacement and the need for a highly treated effluent to ensure that the target microorganisms are not shielded from the UV radiation (i.e., any solids present in the treated effluent may protect microorganisms from the UV light).

Ozone O_3 is generated by passing oxygen (O_2) through a high voltage potential resulting in a third oxygen atom becoming attached and forming O_3 . Ozone is very unstable and reactive and oxidizes most organic material it comes in contact with, thereby destroying many pathogenic microorganisms. Ozone is considered to be safer than chlorine because, unlike chlorine which has to be stored on site (highly poisonous in the event of an accidental release), ozone is generated onsite as needed. Ozonation also produces fewer disinfection by-products than chlorination. A disadvantage of ozone disinfection is the high cost of the ozone generation equipment and the requirements for special operators.

4. BIOLOGICAL TREATMENT PROCESS

Biological treatment of sewage is a two-stage process consisting of

- *Nitrification*
- *Denitrification*

Nitrification is the a biochemical process of removal of nitrogen from wastewater through a biological oxidation of ammonia (NH_4^+) into nitrite (NO_2^-) and continued oxidation of nitrite into nitrate (NO_3^-).

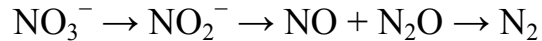
This process involves two different types of bacteria - Nitrosomonas that converts ammonia into nitrite and Nitrobacter that converts nitrite into nitrate as follows:





The second stage of biological treatment of wastewater is the denitrification. The process takes place under conditions when consumption of oxygen exceeds supply, also known as *anoxic* process.

Denitrification is two-step process in which nitrate is converted to nitrite then to nitric oxide (NO) and nitrous oxide (N₂O) and finally to nitrogen (N₂):



5. FACTORS DEFINING QUALITY OF WASTEWATER TREATMENT PROCESS.

The most important factors that determine quality of wastewater treatment process are:

- ***Biological Oxygen Demand (BOD) and Dissolved Oxygen level***
- ***pH level***
- ***Turbidity.***

Fundamentals and methods of measurement are described below.

6.1 Biological Oxygen Demand (BOD) testing

To insure stable wastewater treatment process, microorganisms must be provided with food (different forms of carbon) and oxygen. At the same time effluent discharged into environment must contain level of organic matter low enough to meet regulatory requirements. Therefore, rate of change of dissolved oxygen in water called Biological Oxygen Demand (BOD) can be an indicator of water pollution. BOD is measured in mg/L, which is most commonly used, or parts per million (ppm). Comparison between BOD in influent and effluent is a good indicator of the efficiency of the wastewater treatment plant. For example, in a typical residential city raw sewage has a BOD value of around 300 mg/L. If the effluent from the sewage treatment plant has a BOD of about 30 mg/L, the plant has removed 90 percent of the BOD. The method of measuring BOD approved by US Environmental Protection Agency (USEPA) is the dilution method.

Dilution BOD test is conducted by diluting samples of activated sludge with oxygen saturated de-ionized water with amount of dissolved oxygen measured at the beginning of the test. Sealed samples are kept at 20°C (68°F) for five days in the dark to prevent photosynthesis. Difference between the final DO and initial DO is called BOD₅. Loss of dissolved oxygen indicates amount of organic matter

in the water. The above discussion shows importance of accurate measurement of dissolved oxygen in wastewater treatment process.

6.1.1 Dissolved Oxygen measurement

There are two methods of measurement of dissolved oxygen

- *Galvanic*
- *Polarographic*

Both systems use electrode system that produce where dissolved oxygen reacts with electrode material and generate electric current. Depending upon the electrode material voltage generated can be higher (measured in V) or lower (measured in mV). If voltage is sufficiently high and does not require external voltage source, the measurement method is called galvanic. When voltage generated by the sensor is low and require external voltage source, the method is called polarographic. Galvanic DO sensors have the following advantages over polarographic sensors:

- Galvanic sensors are more stable at lower DO levels.
- Galvanic sensors do not require external voltage source and require less often replacement membrane and electrolyte, thus having lower maintenance cost.

Galvanic DO sensor consists of the following components:

- Anode and cathode immersed in electrolyte
- Oxygen permeable membrane that separates anode and cathode from water.

Galvanic DO sensor operates as follows:

- Oxygen interacts with electrodes which generates voltage (in mV) proportional to pressure of oxygen diffused between them. Higher water flow allows more oxygen to permeate through the membrane, thus generating higher current.
- Current flows through the thermistor. Thermistor is a semi-conductor component that changes its resistance with temperature. The resistance change is required to compensate for changes of the membrane permeability due to water temperature changes.

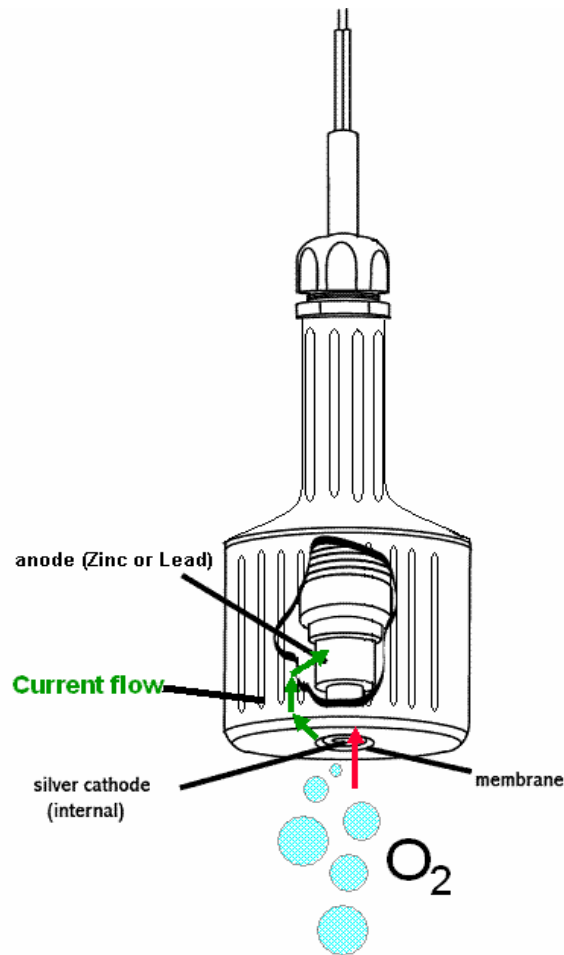


Figure 3. Dissolved Oxygen Sensor

- To represent sensor output in mg/L or ppm, water temperature must be known. An additional thermistor is used to measure water temperature.

6.2 Fundamentals of pH

6.2.1 Introduction

One of the most important factors of wastewater treatment a level of acidity or alkalinity of the discharged effluent. There is only a small “window” within which acidity or alkalinity of water may change without harming living things.

6.2.2 Definition of pH

Since water molecules are in constant motion even at lower temperatures, they collide. At collision, hydrogen ion (H^+) from one molecule is transferred to another molecule and the molecule that loses a hydrogen ion turns into negatively charged hydroxide ion (OH^-).

Reaction of water dissociation can be written as follows:



In pure water at 25°C concentration of hydrogen and hydroxide ions is 1×10^{-7} in mol/L. When one or more of one ion is added to the solution, the concentration of the other decreases. This relationship can be described as follows:

$$[H^+][OH^-] = k_w$$

where

$$k_w - \text{water dissociation constant, } (M/l)^2$$

Aqueous solutions with higher concentration of hydrogen ions are called **acidic solutions**, while aqueous solutions with higher concentration of hydroxide ions are called **basic** or **alkaline solutions**.

pH is defined as **negative logarithm of hydrogen ion concentration** and can be expressed as

$$pH = -\log[H^+]$$

where

$$H^+ - \text{hydrogen ion in mol/L}$$

Value of pH ranges from 0 to 14 where values below 7 exhibit acidic properties and values above 7 exhibit basic or alkaline properties.

6.2.3 pH Measurement

Measurement of solution pH level is based on modified Nernst equation:

$$E = E_0 + (1.98 \times 10^{-4})T \text{ pH}$$

Where E – voltage generated by the pH sensing electrode (mV)

E_0 – voltage generated by the standard electrode (mV)

T – absolute temperature, Kelvin scale

As Nernst equation indicates, there is a linear relationship between temperature and voltage output of the pH sensor. Temperature affects measurement in two ways. First, any change of the temperature affects dissociation constant K_w in the solution being measured, therefore changing pH value in the solution. The second reason that temperature affects the pH measurement is glass electrode resistance. As temperature of the measured solution rises, the resistance across the glass bulb decreases.. This change in resistance is constant and can be calculated for a glass specific formulation of the electrode, requiring use of temperature compensation in measuring system. Typical change of the resistance drop is ten times per every 30°C rise. Additional factors that influence the electrode resistance are glass formulation, glass thickness and shape of the electrode tip.

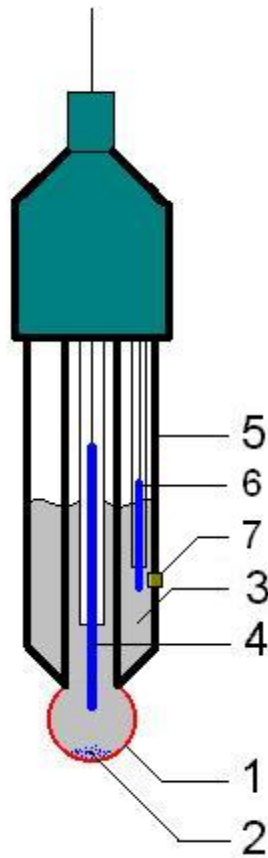
Typical pH sensor consists of two electrodes:

- ***Measuring electrode***
- ***Reference electrode***

Measuring electrode is a glass bulb coated with thin layer of hydrated gel inside and out separated by a layer of dry glass, with silver wire (Ag) coated with silver chloride (AgCl) serving as sensing electrode. The atomic structure of the glass bulb is shaped in a way that allows sodium ions (Na^+) in the hydrated gel to migrate out of the glass into solution, while hydrogen ion (H^+) can diffuse in and out of hydrated gel. In alkaline solution, hydrogen ion migrates out the gel and negative charge is developed on outer gel layer. In acidic solution, hydrogen ion migrates into gel thus changing its charge to positive. Since polarity of the reference electrode does not change, voltage measured between two electrodes changes its value and polarity depending upon pH level of measured solution.

In order for measuring electrode to provide an accurate pH measurement, the reference electrode must have constant and stable potential. Any deviations in reference electrode potential will cause changes in output signal thus causing error in pH measurements. Reference electrode consists of silver (Ag) wire, coated with silver chloride (AgCl) immersed into potassium chloride (KCl) solution that has low electrical resistance. The reference wire must be electrically connected to the solution that is being measured. This is accomplished by porous reference or the “salt” junction. The structure of the reference junction is designed to allow very small amount of electrolyte to leak into solution being measured.

The illustration above shows typical design of pH sensor



1. Measuring electrode bulb
2. Silver chloride precipitate
3. Solution of potassium chloride (KCl)
4. Measuring electrode sensing wire
5. Sensor body
6. Reference electrode, sensing wire
7. Reference junction

Figure 4. pH Sensor

6.3 Fundamentals of Turbidity

One of important water quality indicators is a amount of suspended solids. Suspended solids obstruct transmittance of light through water, thus providing a qualitative characteristic known as *turbidity*.

American Water Works Association (AWWA) *Standard Methods for the Examination of Water and Wastewater* describes turbidity as light scattering due to suspended particles in water. Measuring of this scattering effect allows us to quantify clarity of water.

6.3.1 Turbidity unit

To measure turbidity, solution of known and repeatable clarity was required, which led to development of formazin. Formazin is a polymer that consists of chains of different lengths and random configuration. While chains length and configuration are random, the light scatter is very reproducible. This reproducibility allows preparing standard solutions of different clarity to be measured in *nephelometric turbidity units* (NTU).

6.3.2 Turbidity measurement

Development of formazin allowed industry to develop instruments for measuring turbidity that called *nephelometer* that measures amount of scattered light at 90° relative to a light source. Modern nephelometers are required to measure turbidity over wide range from below 1 NTU (drinking water) to hundreds NTUs.

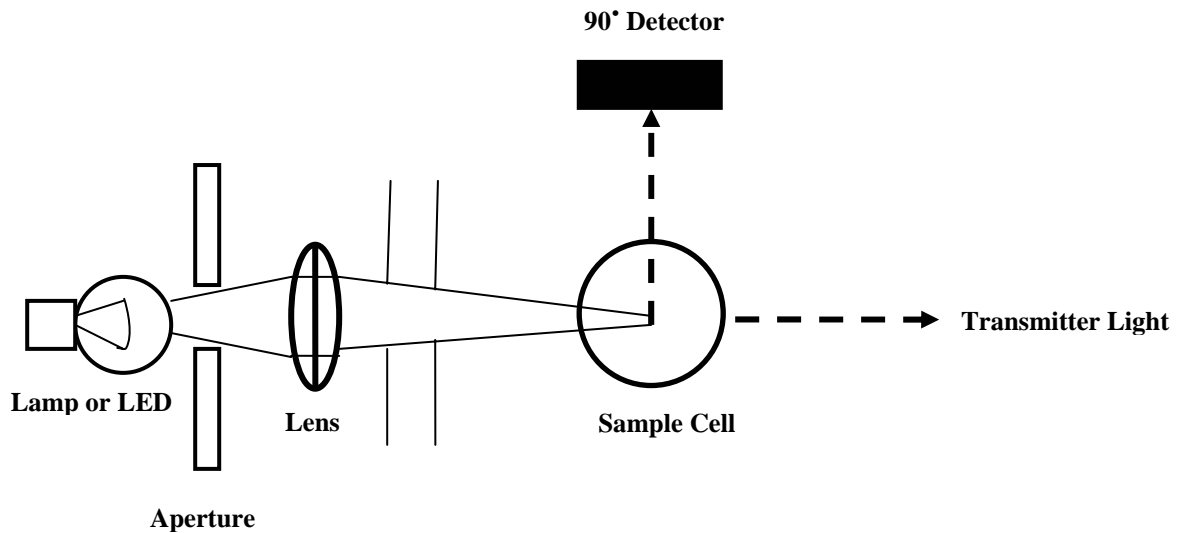


Figure 5. Optical design of turbidity meter

Typical nephelometer consists of the following components:

- *Light source*
- *Light detector*
- *Optics*

There are two main light sources used in modern nephelometers: incandescent lamps with tungsten filament and light emitting diode (LED). Incandescent lamp

has wide spectral output that is function of supply voltage. Therefore, to produce stable spectral output, incandescent lamp requires regulated power supply. On the other hand, LED is a device that produces visible light within narrow spectral band. Application of LED in nephelometry is expanding because LED has much lower power consumption and much longer operational life than incandescent lamp and does not require regulated power supply.

Light detecting device in nephelometer captures and measures intensity of scattered light. The most commonly used light detector in modern nephelometers is photodiode. Photodiode is a semiconductor device that generates current proportional to intensity of light. Photodiode consists of p-n junction and as in some models separated by intrinsic (undoped) layer called p-i-n junction. When a photon with sufficient energy is absorbed by depletion or intrinsic region, it generates an electron-hole pair. Field forces of depletion region move holes and electrons from the p-n or p-i-n junction toward electrodes. Thus, as holes move toward anode and electrons toward the cathode, a photocurrent is generated. Photodiodes operate in two major modes:

- ***Photovoltaic***
- ***Photoconductive***

In photovoltaic mode, which is a zero bias mode, flow of photocurrent is restricted by “dark current” that flows across the junction in direction opposite to photocurrent. Photovoltaic mode has the following disadvantages: relationship between light intensity and output voltage is non-linear, relatively high response time and small dynamic range.

In photoconductive mode, small reverse bias is applied to photodiode. In this mode response time is significantly reduced and its output becomes linear.

Table below summarize properties of materials used to manufacture of typical photodiode

Material	Dark Current	Speed	Wavelength Range (nm)	Relative cost
Silicon (Si)	Low	High	400-1000	Low
Germanium (Ge)	High	Low	900-1600	low
Indium Gallium Arsenide Phosphide (InGaAsP)	Low	High	1000-1350	High
Indium Gallium Arsenide (InGaAs)	Low	High	900-1700	High

The third component that affects performance of the turbidimeter is optics. Typical turbidimeters that are used in water and wastewater processes use 90° detection angle that offers lower sensitivity to variations in size of particles simple optic system with very low stray light. Stray light is major source of error in low level turbidity measurements. There are several sources of stray light, such as sample cell with scratches, defective or imperfect surfaces, reflections within optical system, etc. In order to minimize stray light, optical systems with black mirrors and light traps are used. However, the most significant source of stray light that is dust contamination of optical system that cannot be eliminated by design improvements. Over time as dust contamination generates additional light scattering, thus creating turbidity measurement error. Another important factor that influences performance of turbidity meter is path length. The path length affects both sensitivity and linearity of the instrument. Sensitivity increases as path length increases, while linearity decreases due to multiple scattering and absorbance. As path length decreases, linearity range increases, but sensitivity especially at low particle concentration drops. In addition to that, stray light error also raises.

To improve performance characteristics such as good stability, linearity, sensitivity, low stray light and color rejection a new type of nephelometer has been developed by Hach Company. This device called Ratio™ is based on calculating ratio between transmitted light, forward scattered light and 90° scattered light. Ratio turbidimeter operates as follows:

1. Large transmitted-light detector measure light passing through the sample
2. Forward scattered detector measures light, scattered at 30° from transmitted direction
3. A 90° detector measures light scattered from the sample normal to the light beam.
4. Signals from these detectors are processed to calculate turbidity

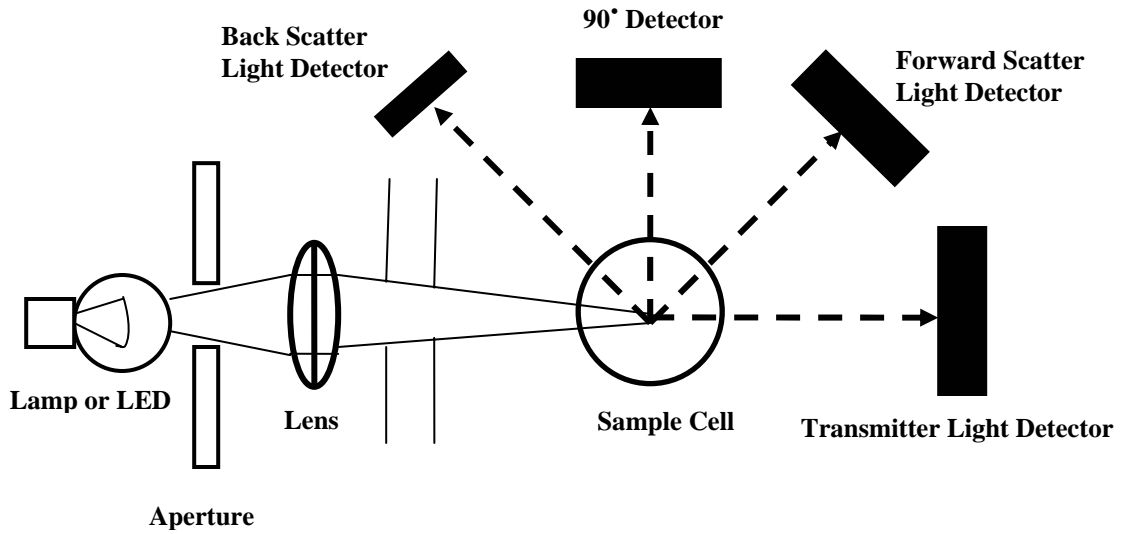


Figure 6. Optical design of ratio turbidity meter

Models that are design to measure very high turbidity also have a back scattered light detector. Low stray light is achieved by mounting 90° detector above horizontal plane. This instrument is designed to have two algorithms to calculate turbidity:

- *Ratio Turbidity*
- *Non-Ration Turbidity*

Ratio turbidity algorithm is defined as follows:

$$T = I_{90} / (d_1 I_1 + d_2 I_2 + d_3 I_3 + d_4 I_{90})$$

where

- T – turbidity in NTU units (0-10,000)
- d₁, d₂, d₃, d₄ – calibration factors
- I₉₀ – 90° scattered light detector current
- I₁ – transmitted light detector current
- I₂ – forward scattered light detector current
- I₃ – back scattered light detector current when applicable

Non-Ration turbidity algorithm is defined as follows:

$$T = a_0 I_{90}$$

where

T – turbidity in NTU units (0-40)

a_0 – calibration factor

I_{90} – 90° scattered light detector current

7. Summary

When used with domestic wastewater, Membrane Bioreactor processes could produce effluent of quality high enough to be discharged to coastal, surface or brackish waterways or to be reclaimed for urban irrigation. Other advantages of Membrane Bioreactors over conventional processes include small footprint, easy retrofit and upgrade of old wastewater treatment plants.

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