

ENVE 424

Anaerobic Treatment

Lecture 10

Anaerobic Sludge Digestion

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Sludge digestion

- ❖ AD is used to stabilize both primary & secondary sludges having a solids content of between 2-6% (20-60 gTS/l).
- ❖ About 70% of the mixed sludge is degradable and up to 80% of it is digested reducing the TS by about 50%.
- ❖ Mixed sludge is rich in carbohydrates, lipids and proteins.
- ❖ Although it contains a variety of anaerobic bacteria, in order to obtain the correct balance between acidogens and methanogens the raw sludge needs to be seeded.

Composition of sewage sludge

Typical composition of sewage sludges before and after digestion
(g per 100g total solids)

Constituent	Raw sludge	Digested sludge
Suspended solids	95	97
COD	140	100
Organic carbon	40	31
Organic matter	60–80	45–60
Greases and fats	7–35	3.5–17
Cellulose	4	0.6
Hemicelluloses	3	1.6
Lignin	6	8
Protein	22–28	16–21
Anionic detergents	0.5–1.5	0.7–2.2

Thermophilic Digestion

- ❖ Most high-rate digesters are operated in the range 30 to 38°C.
Bacteria that grow in this temperature range are called mesophilic.
- ❖ Another group of microorganisms, called thermophilic bacteria, grow in the temperature range 50 to 57°C.
- ❖ Thermophilic anaerobic digestion has been studied since the 1930s, at both the laboratory and plant scales.

Thermophilic Digestion

❖ **Advantages:**

- ❖ Faster reaction rates, which permit increased VS destruction.
- ❖ Increased destruction of pathogens.

❖ **Disadvantages:**

- ❖ Higher energy requirements for heating
- ❖ Lower-quality supernatant, containing large quantities of dissolved materials
- ❖ Higher odor potential
- ❖ Poorer process stability because thermophilic bacteria are more sensitive to temperature fluctuations.
- ❖ Poor dewaterability

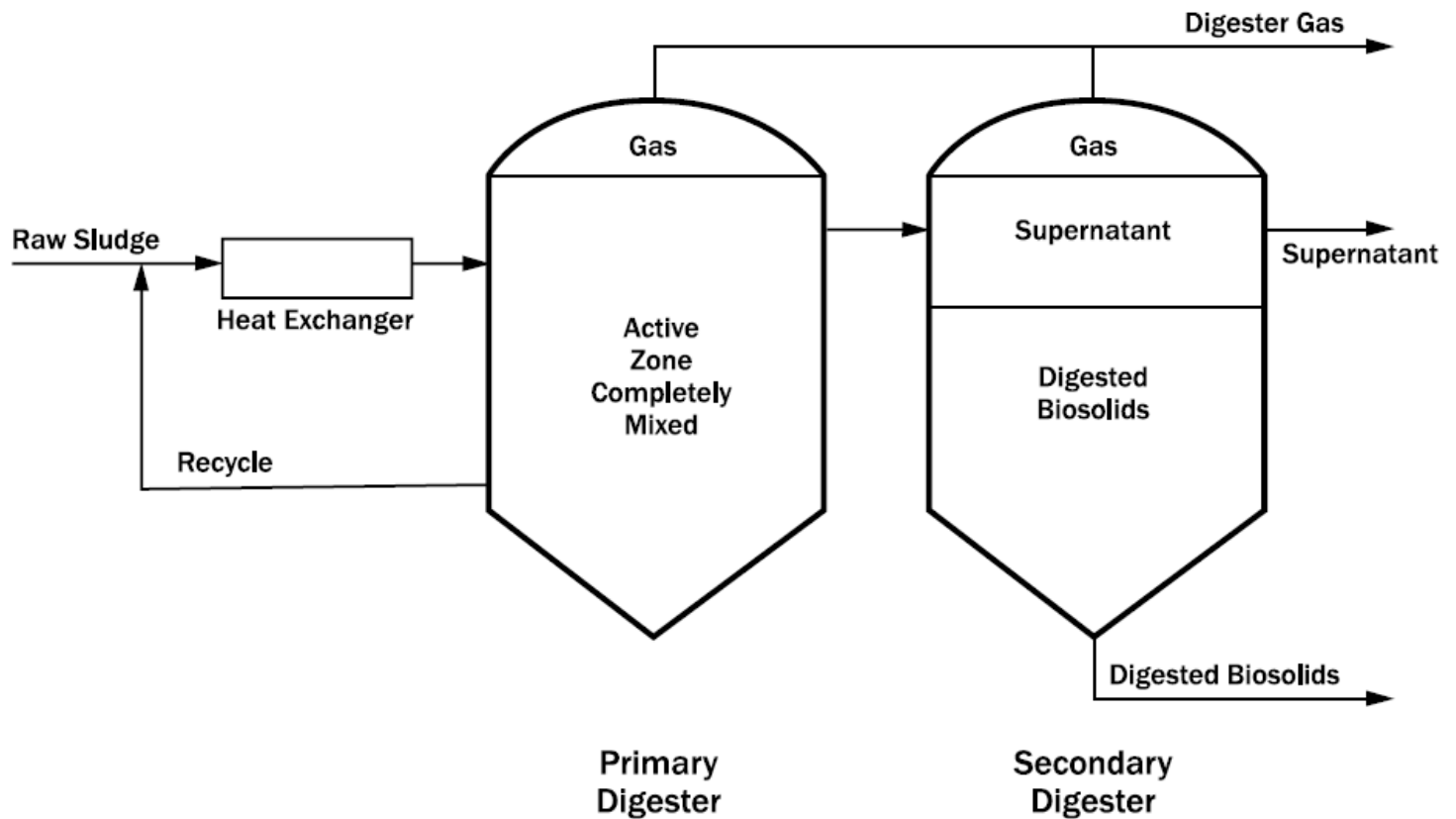
Two Stage Digestion

- ❖ Two-stage digestion is carried out in a high-rate digester coupled in series with a second tank which is neither heated nor mixed.
- ❖ Its main function is to allow gravity concentration of digested solids and decanting of supernatant liquor.
- ❖ Decanting reduces volume of digested sludge, requiring further processing and disposal.
- ❖ The second tank fitted with a floating cover can also provide storage for digested sludge and digester gas.

Two Stage Digestion

- ❖ Very little solids reduction and gas production take place in the second tank.
- ❖ Many secondary digesters have performed poorly as thickeners, producing dilute sludge and high-strength supernatant.
- ❖ This is because some gas will come out of the solution in small bubbles if there is incomplete digestion in the primary digester or if the sludge transferred from the primary digester is supersaturated with gas.

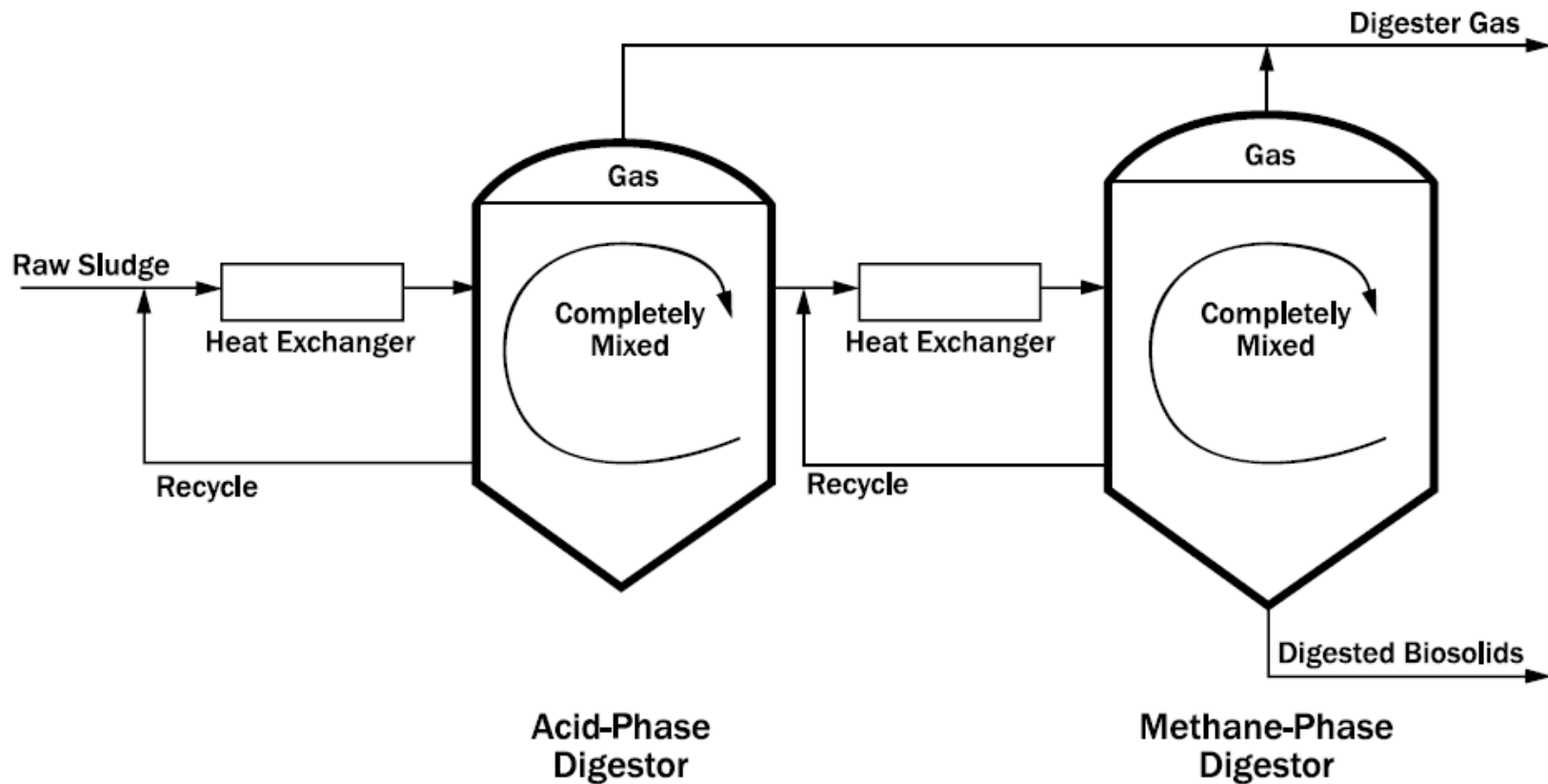
Two Stage Digestion



Two Phase Digestion

- ❖ In two-phase digestion, acidogenesis & methanogenesis phases are divided into separate tanks coupled in series.
- ❖ The 1st reactor (acid-phase digester) is for hydrolysis and acidogenesis and is designed for 1-2 day SRT.
- ❖ It can be mesophilic or thermophilic. pH is between 5.5 and 6.5. Methane generation is negligible.
- ❖ 2nd reactor (methane-phase digester) is designed for about 10 days of SRT and operates in mesophilic temperature range.

Two Phase Digestion



Advantages of 2-Phase Digestion

- ❖ Higher volatile solids reduction because it allows the creation of an optimum environment for the acid formers
- ❖ Increased production of gases
- ❖ Higher content of methane in the final product gas
- ❖ Higher pathogen reduction
- ❖ Fewer foaming problems
- ❖ Better stability of the digestion process

Process Design

- ❖ Determination of digester tank volume is the first important consideration in the design of an AD system.
- ❖ Various methods have been used to determine the size of the digester, including solids loading, solids retention time, volumetric loading and volatile solids destruction.
- ❖ Other design considerations, such as mixing, heating, energy recovery and chemical additions, should also be evaluated in the design of the digestion system.

Design Criteria

Typical Design Criteria for Mesophilic Anaerobic Sludge Digesters

Parameter	Units	Value
Volume criteria		
Primary sludge	m ³ /capita	0.03–0.06
Primary sludge + trickling filter sludge	m ³ /capita	0.07–0.09
Primary sludge + waste activated sludge	m ³ /capita	0.07–0.11
Solids loading rate	kg VSS/m ³ ·d	1.6–3.2
Solids retention time	d	15–20
Sludge concentration		
Primary sludge + biological sludge feed	%	4–7
Digested sludge draw-off ^a	%	4–7

Solids loading rate

- ❖ A more direct design criterion in determining digester volume is the volatile solids (VS) loading rate.
- ❖ It is the mass of volatile solids fed to the digester per unit volume and time ($\text{kgVS}/\text{m}^3\cdot\text{day}$).
- ❖ Design loading criteria are based on sustained loading conditions: typically, peak month solids production.
- ❖ Excessively low VS loading criteria would result in a large digester system, which can be expensive to operate because it may not produce sufficient gas to provide the energy needed to heat digester to desired temperature.

Solids retention time

- ❖ Solids Retention Time (SRT) is the average time the microbial mass is retained in the digester.
- ❖ For high-rate AD systems without recycle, SRT is equal to HRT and can be calculated based on either the sludge feeding rate or the removal rate.

$$\text{SRT (days)} = \frac{\text{Mass of solids in the digester (kg)}}{\text{Mass of solids withdrawn daily (kg/day)}}$$

Solids retention time

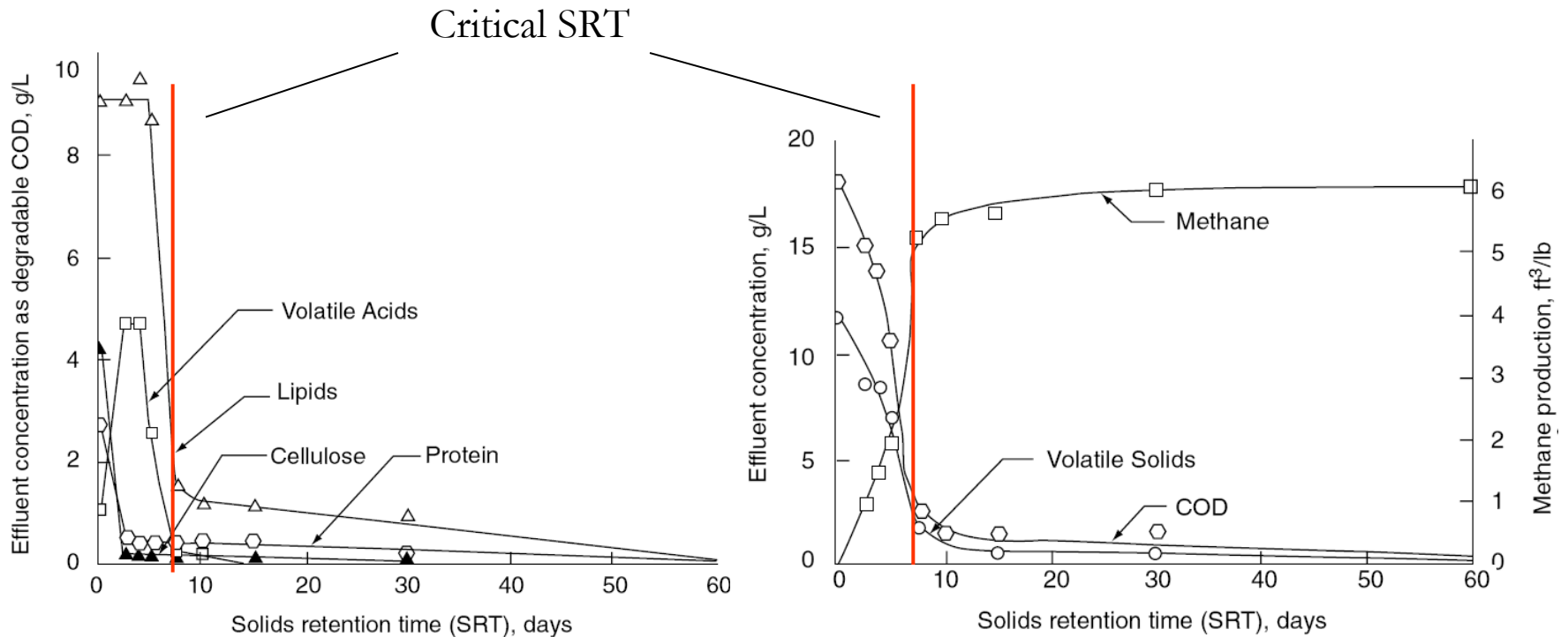
- ❖ Theoretically, SRT can be as low as 10 days for a high-rate sludge digester operating at 35°C.
- ❖ However it is common practice to use >20 days as the design SRT to allow for variation in daily sludge loading.
- ❖ With the improvements in mixing and heating, a 15 day SRT may allow an adequate safety margin to cover most operational difficulties.

Solids retention time

Suggested Solids Retention Time for a High-Rate Digester

Operating Temperature		Critical SRT (days)	Minimum Design SRT (days)
°C	°F		
18	65	11	28
24	75	8	20
30	85	6	14
35	95	4	10
40	105	4	10

Solids retention time

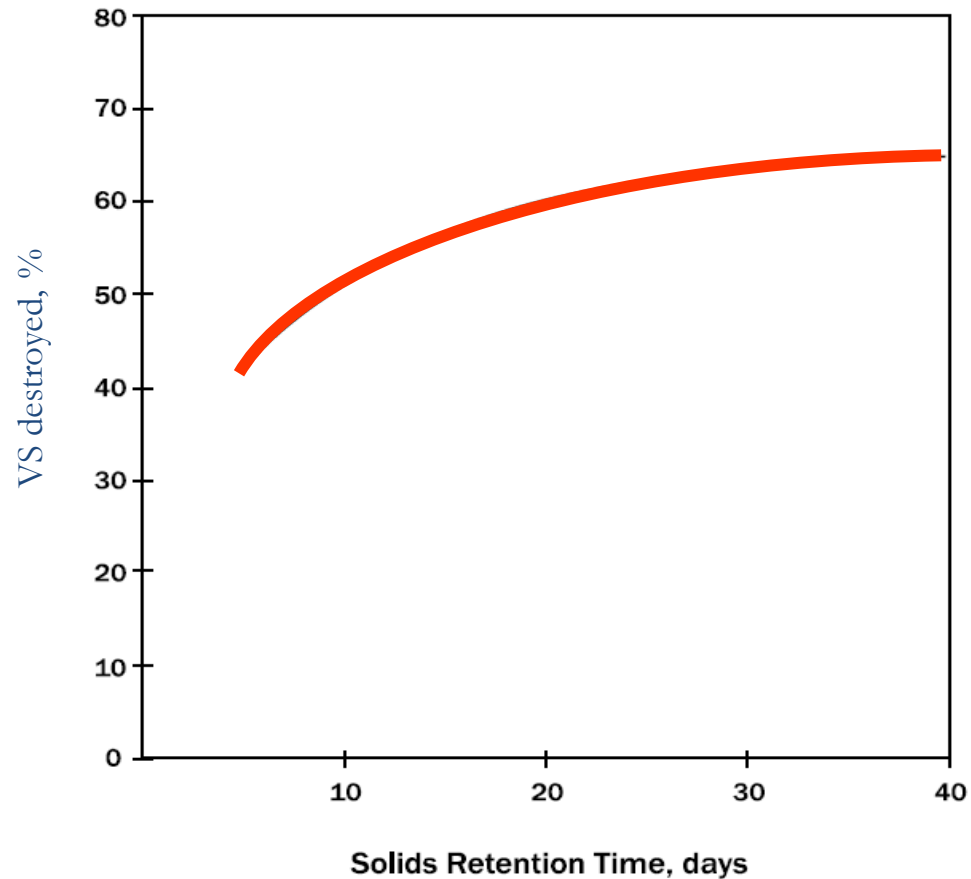


Critical SRT is the breakpoint where the rate at which bacteria leave the system exceeds their rate of reproduction (washout begins)

Volatile solids reduction

- ❖ It is usually assumed that solids reduction takes place only in the volatile portion of the sludge solids.
- ❖ Therefore, the common measure of the degree of stabilization is the percent VS destroyed.
- ❖ VS reduction in high-rate ADs is usually 50- 65%.
- ❖ VS reduction achieved in any particular application depends on both the characteristics of the sludge and the operating parameters of the digestion system.

Volatle solids reduction



Volatle solids reduction as function of solids retention time

Gas production

- ❖ Production of biogas is a direct result of VS destruction.
- ❖ Specific gas production for wastewater sludge generally ranges from 0.8 to 1.1 m³/kg of VS destroyed.
- ❖ If sludge contains a higher percentage of fats and grease as long as adequate SRT is provided for these slow-metabolizing materials gas production will be high.
- ❖ A healthy digestion process produces a gas with about 65-75% CH₄, 30-35% CO₂ and very low N₂, H₂ and H₂S.
- ❖ Lower heating of digester gas is 22.4 MJ/m³ compared to 35.8 MJ/m³ for CH₄ at 1 atm and 20 °C.

Digester tank

- ❖ AD tanks are usually cylindrical or egg-shaped.
- ❖ The most common tank design is a low vertical cylinder 6 to 38 m in diameter with a sidewall depth of 6 to 14 m.
- ❖ Tanks are usually made of concrete, although steel tank designs are not uncommon in smaller sizes.
- ❖ Tank floors are usually conical with slopes between 12-30° and have facilities to withdraw the digested sludge from the base.

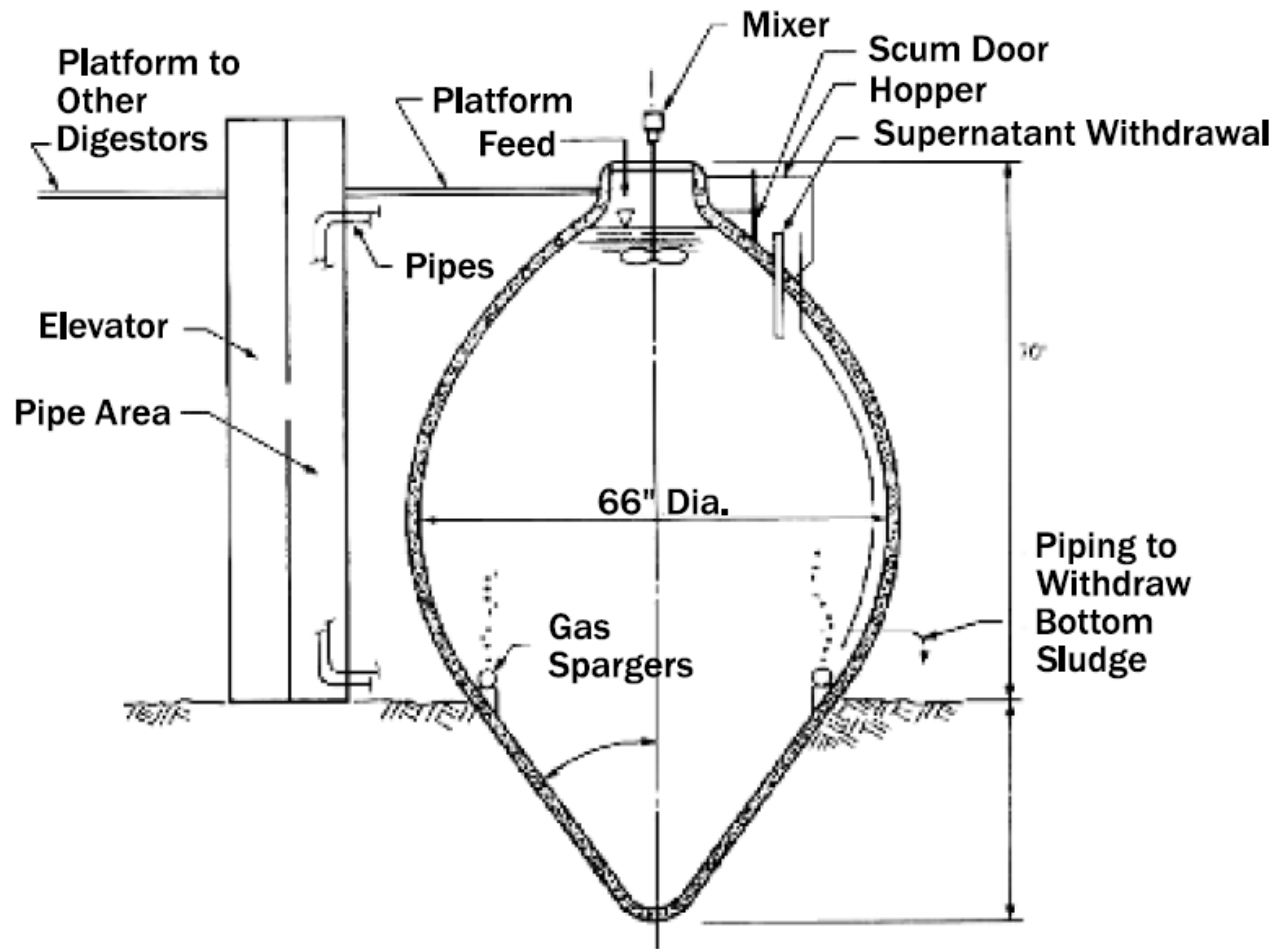
Digester tank

- ❖ Egg-shaped digesters originated in Germany in 1950s.
- ❖ The steeply sloped bottom of the tank eliminates grit accumulation; therefore, cleaning is not required.
- ❖ Liquid surface area at the top is small, so scum can be kept fluid with a mixer and removed through a scum door.
- ❖ Egg-shaped digesters can be built with steel or concrete.
- ❖ Steel construction is more common because concrete construction requires complex formwork and special construction techniques.

Egg-shaped sludge digester



Egg-shaped sludge digester



Digester tank

- ❖ Large digester tanks are built above ground.
- ❖ Smaller ones can be constructed below ground level or surrounded by earth embankments to provide additional insulation.
- ❖ The entire contents of the tank needs to be turned over once every 3-4 hours, with the sludge warmed by heat exchangers using hot water from gas boilers or the cooling systems of gas

engines.

Digester Covers

- ❖ Anaerobic sludge digesters are normally covered with a fixed or floating top for gas collection.
- ❖ Floating covers rise and fall according to volume of gas and sludge and their weight provides the gas pressure.
- ❖ Fixed covers require a separate biogas holder that allows the gas to move freely in both directions.
- ❖ This is particularly important if a vacuum is not to be produced when sludge is removed from the digester.

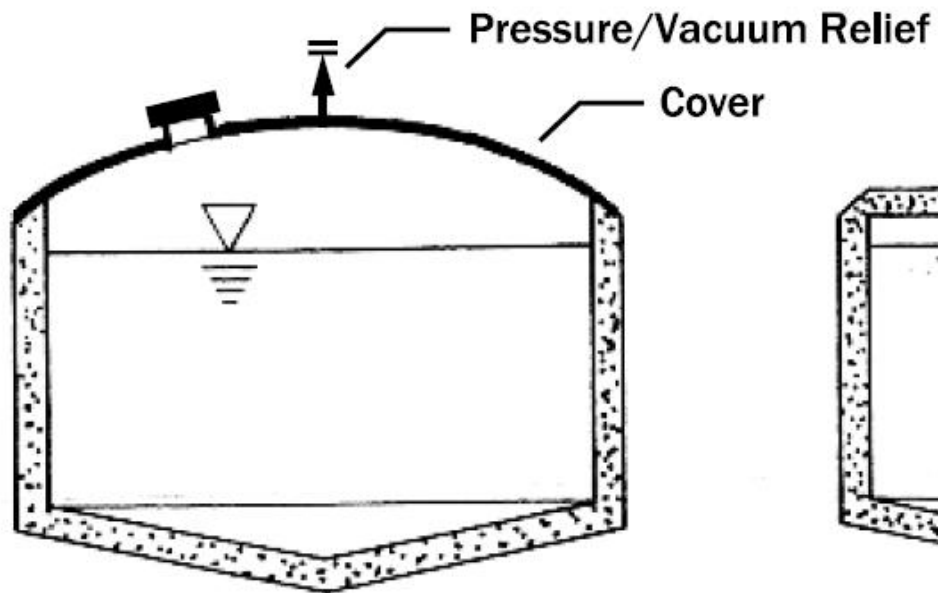
Digester Covers

- ❖ Fixed covers are either dome-shaped or flat and are fabricated from reinforced concrete, steel, or fiberglass-reinforced polyester.
- ❖ Concrete roofs are susceptible to cracking, therefore are sometimes lined with PVC or steel plate to contain gas.
- ❖ Floating covers float on the surface of digester contents and allow the volume of digester to change without allowing air to enter the digester and mix with biogas.

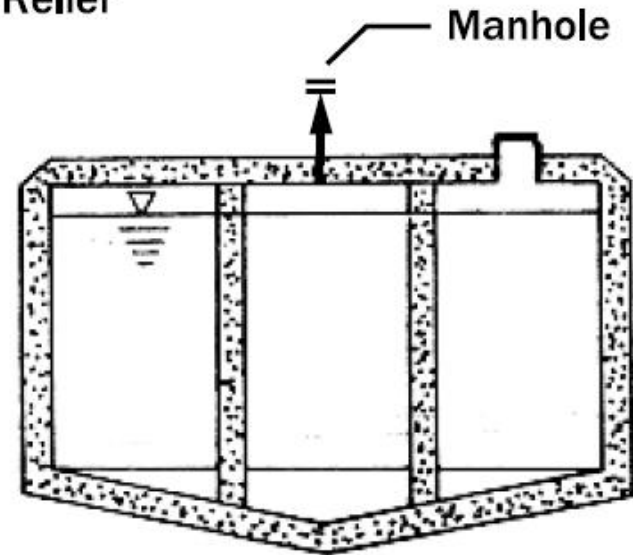
Digester Covers

- ❖ Floating gas holder is a type of floating cover with an extended skirt to allow storage of gas during periods when gas production exceeds demand.
- ❖ A recent development in gas holder covers is the membrane cover.
- ❖ The cover consists of flexible air and gas membranes under a support structure.

Fixed covers

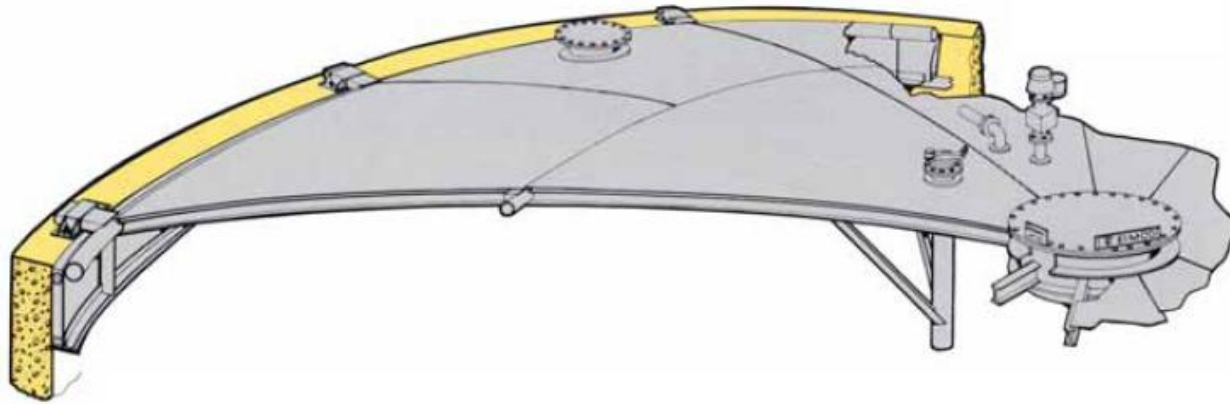


Domed Fixed Cover



Flat Fixed Cover

Fixed covers



Fixed cover AD with gas holder

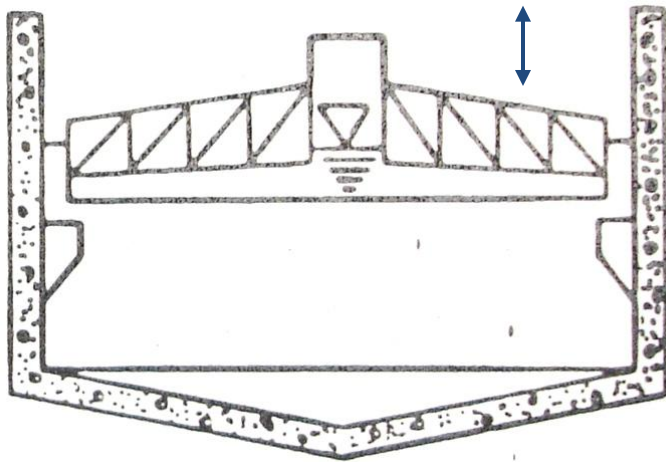


Fixed cover AD with a biogas holder

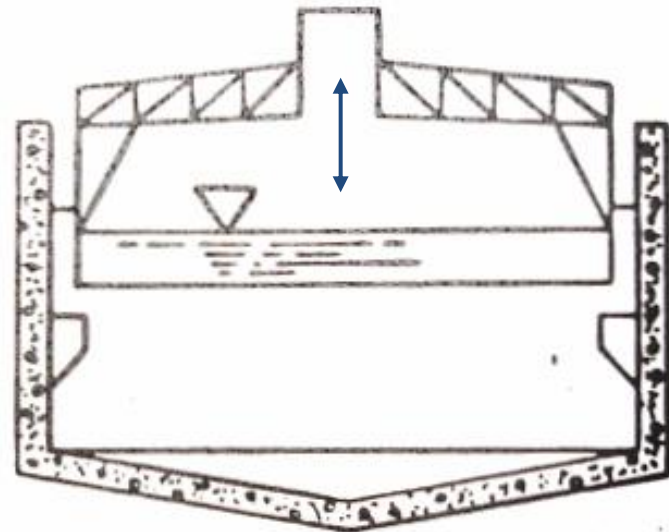


Biogas holder with lightning protection

Floating covers – gas holders



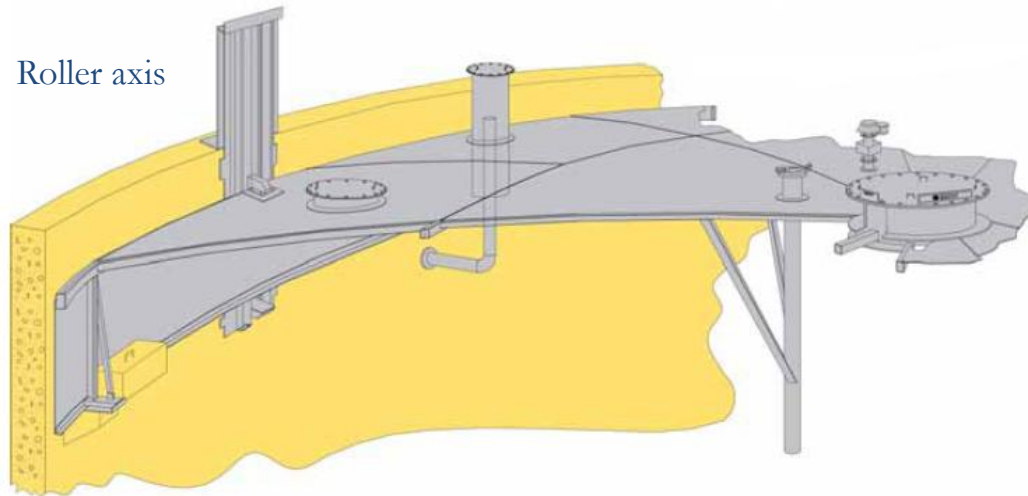
Floating Cover



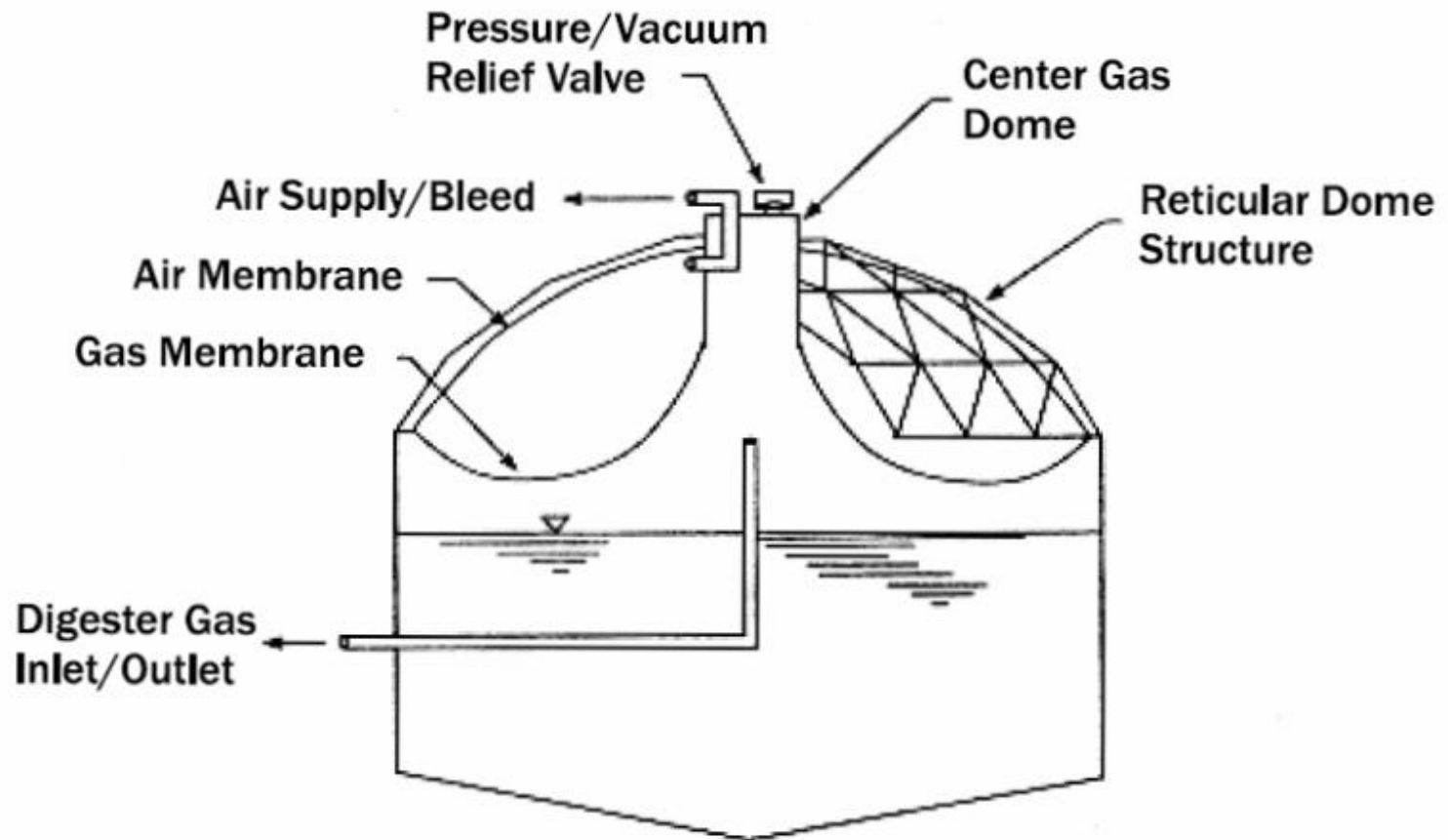
Floating Gas Holder

As gas pressure builds, an increasing amount of cover's total weight is supported by gas and this causes the cover to rise out of the liquid

Floating gas holder



Membrane gas holder



Membrane gas holder



Uniform Feeding

- ❖ Sludge feed is introduced into an AD at frequent intervals to maintain constant conditions in the digester.
- ❖ Continuous or nearly continuous feeding eliminates any abrupt flow rate and organic loading changes that could result in shock loading.
- ❖ Multiple feed points in the digester can also alleviate or reduce shock loadings.
- ❖ Shock loading an AD affects its temperature and dilutes alkalinity necessary for buffering against pH in digester.

Mixing

- ❖ A certain amount of natural mixing occurs in the digester from the rise of gas bubbles and the thermal convection currents created by the addition of heated sludge.
- ❖ However, auxiliary mixing is required to optimize the AD performance.
- ❖ Three types of mixing typically used in ADs are;
 - ❖ Mechanical mixing,
 - ❖ Gas recirculation, and
 - ❖ Pumping

Benefits of mixing

- ❖ Reduces thermal stratification
- ❖ Disperses raw sludge for better contact with active biomass
- ❖ Reduces scum buildup
- ❖ Dilutes any inhibitory substances or any adverse pH and temperature feed characteristics
- ❖ Increases the effective volume of the reactor
- ❖ Allows reaction product gases to separate more easily
- ❖ Keeps in suspension more inorganic material, which has a tendency to settle

Mechanical mixing

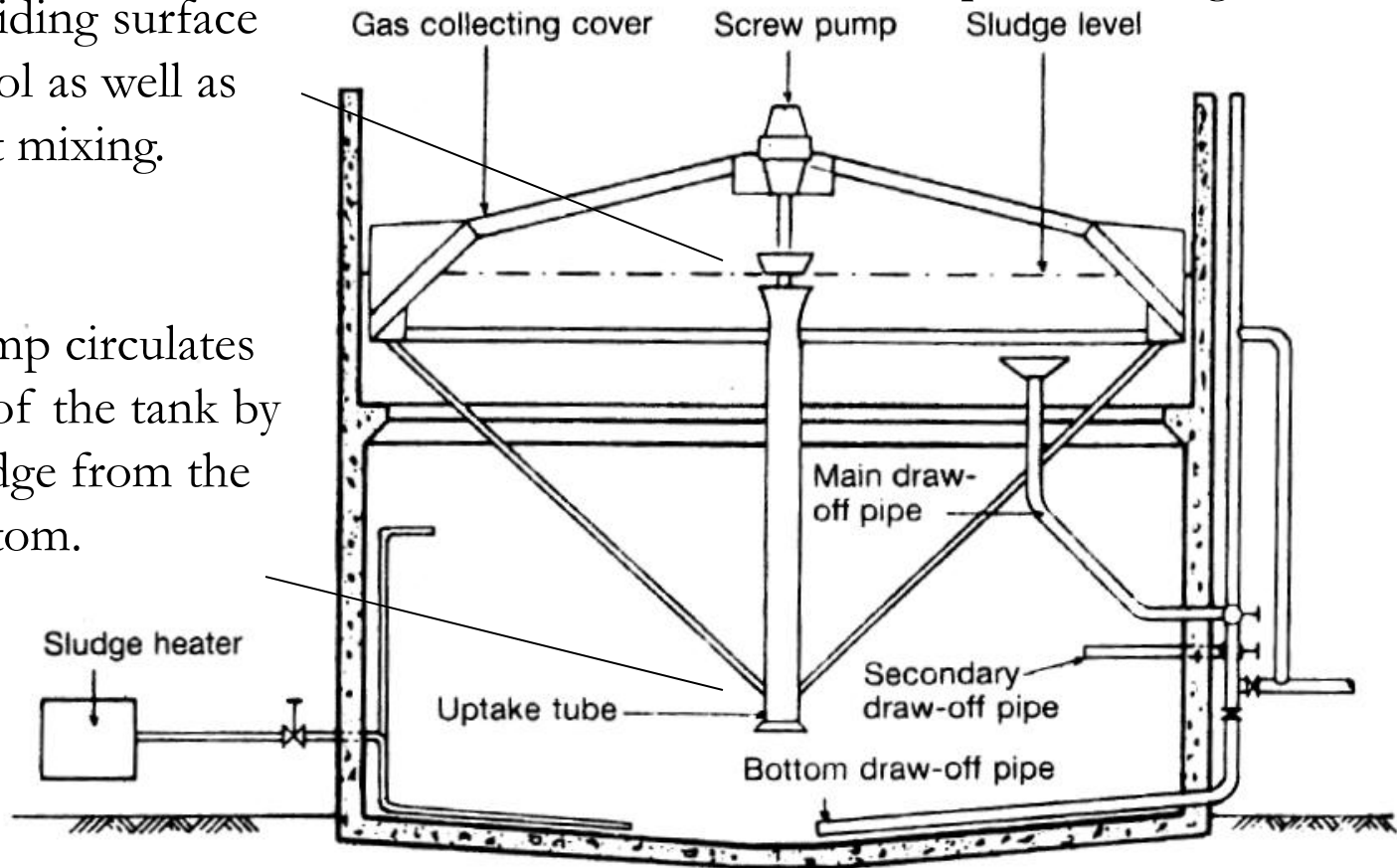
- ❖ Mechanical mixing is performed by low-speed flat-blade turbines or high-speed propeller mixers.
- ❖ In draft tube mixing, a propeller drives sludge through a draft tube to promote vertical mixing.
- ❖ Draft tubes can be either internally or externally mounted.
- ❖ Mechanical mixing provides good mixing efficiency and break up of any scum layer.
- ❖ However, rags in sludge can foul impellers.
- ❖ Efficient mechanical mixing can be effected with about 0.007 kW/m^3 of digester volume.

Draft tube mixing

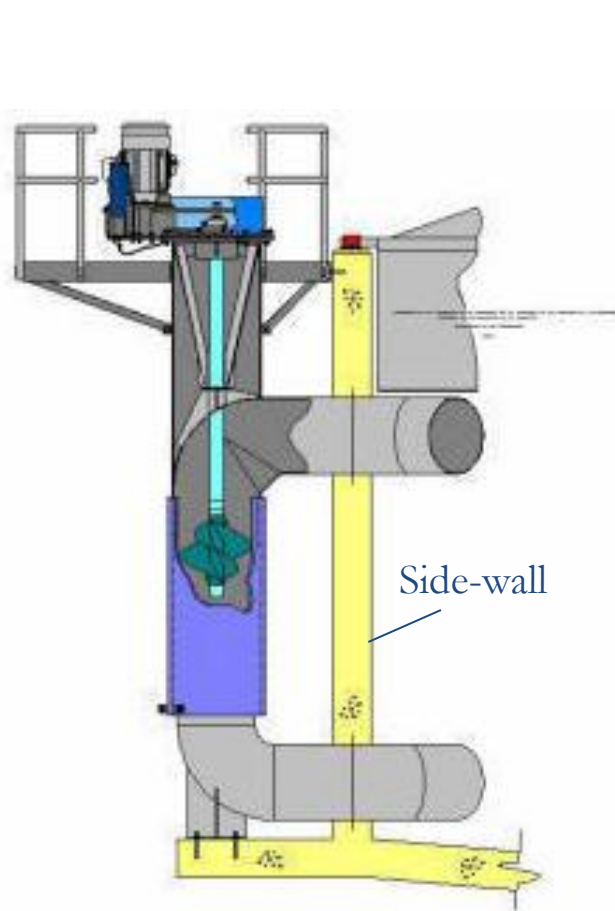
2. Then spray it over the surface providing surface scum control as well as efficient mixing.

1. Screw pump circulates the contents of the tank by drawing sludge from the bottom.

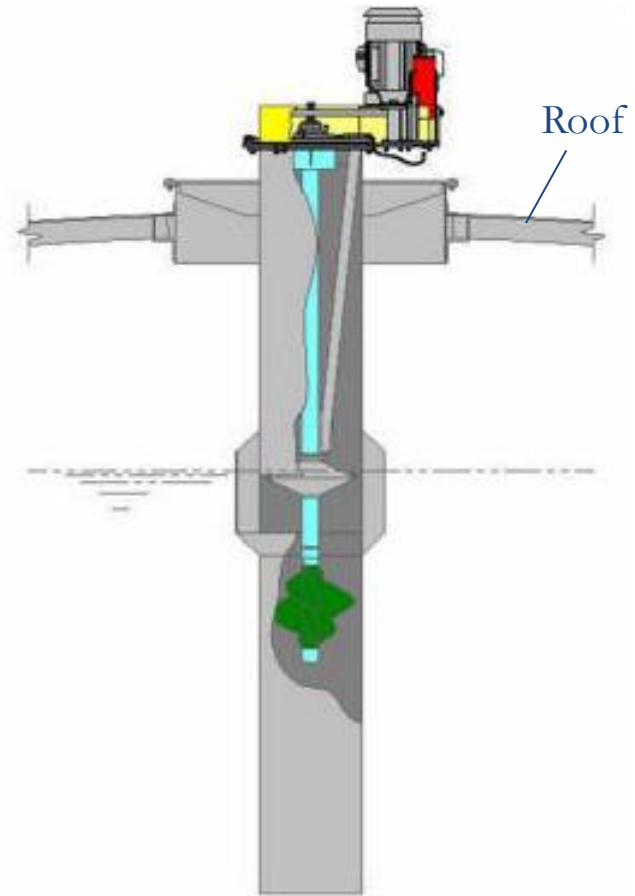
3. At regular intervals, pump is reversed for a short period to prevent blockages & improve mixing.



Draft tube mixing

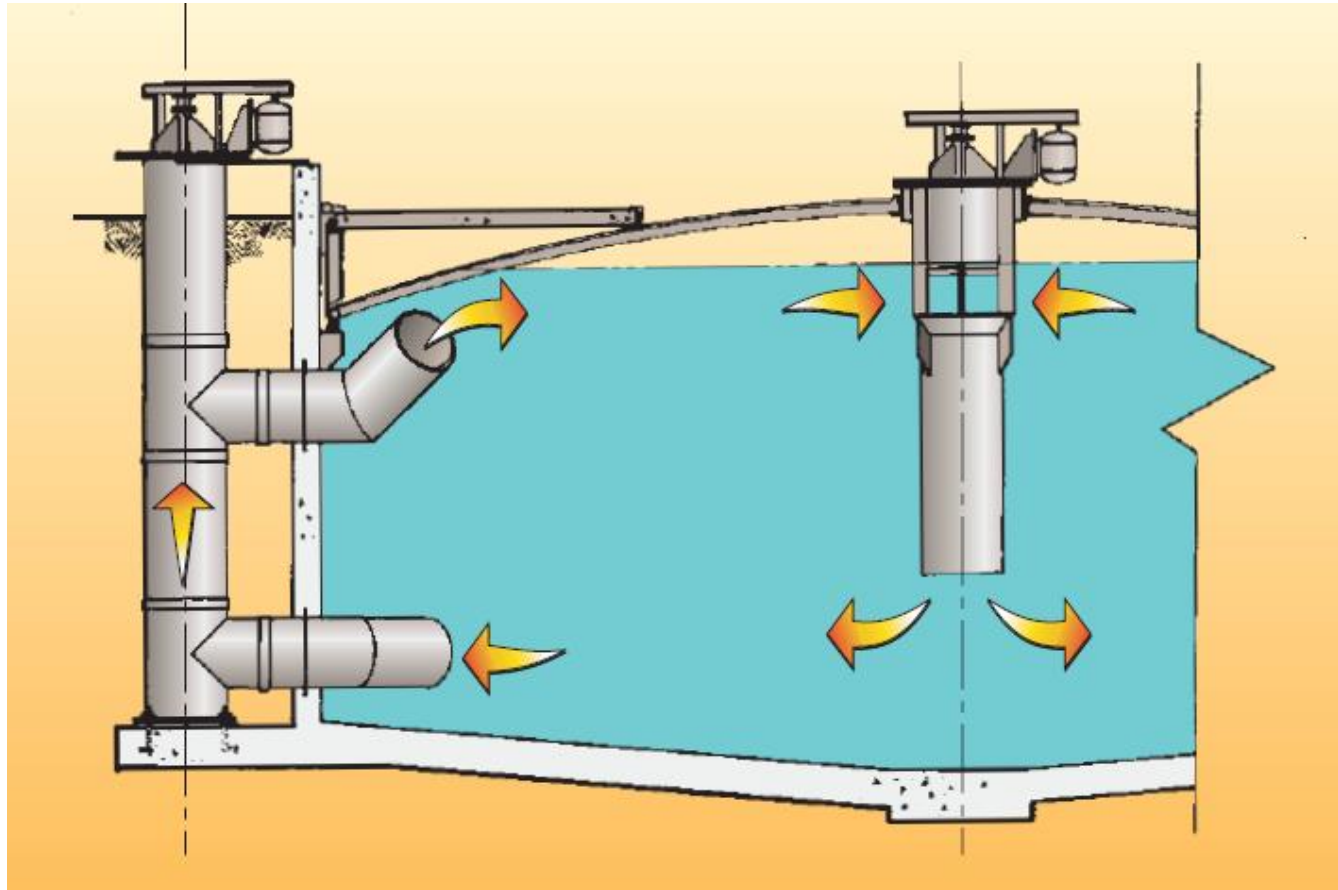


External draft tube



Roof mounted draft tube

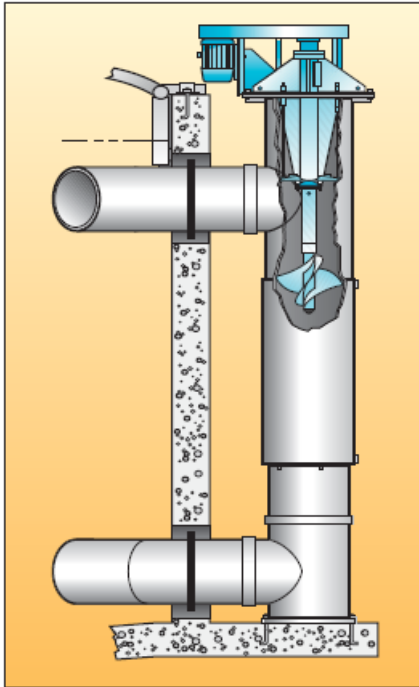
Draft tube mixing



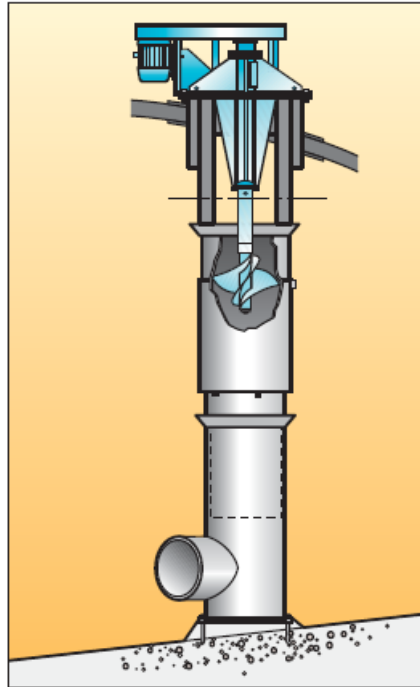
Marmara Üniversitesi
External draft tube

Roof mounted draft tube

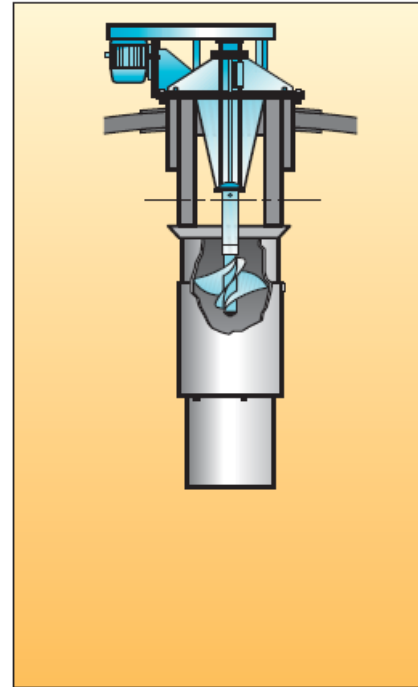
Draft tube mixing



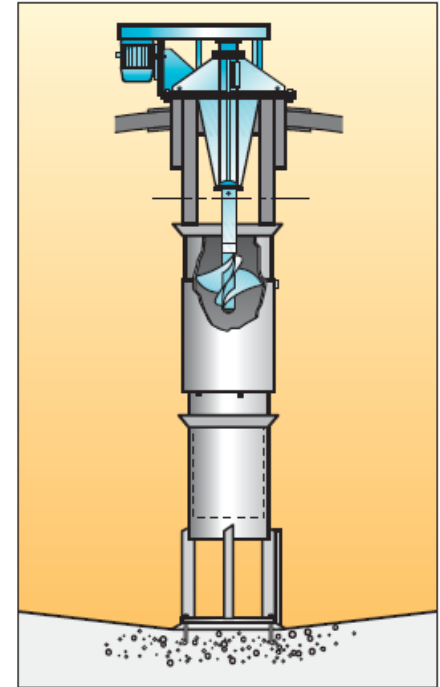
External draft tube



Roof mounted
Type I



Roof mounted
Type II



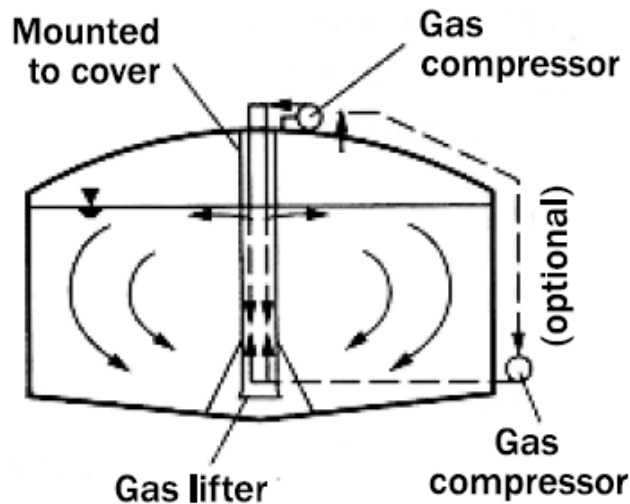
Roof mounted
Type III

Mixing with gas recirculation

Four different methods are used in gas mixing;

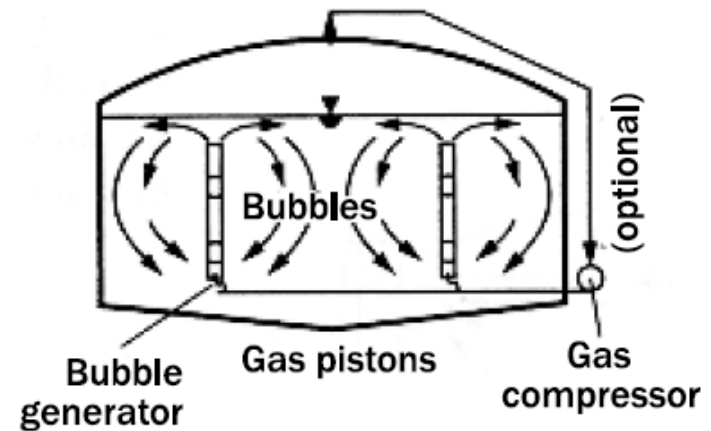
- ❖ Confined injection of gas bubbles intermittently at the bottom of pistons to create piston pumping action and surface agitation
- ❖ Confined release of gas within a draft tube positioned inside a tank
- ❖ Unconfined injection of gas through a series of lancers suspended from the digester cover
- ❖ Unconfined release of gas through a ring of spargers (diffusers) mounted on the floor of the digester.

Gas recirculation



Draft Tube System

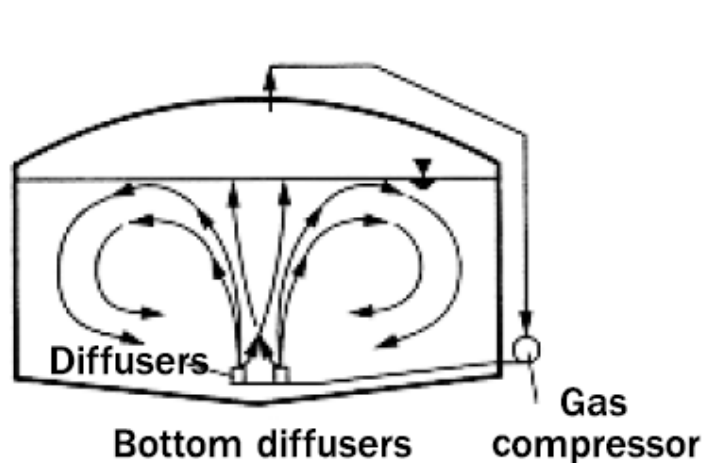
Tube acts as a gas lift pump, causing flow of sludge entering bottom of tube to exit at top. This confined method induces bottom currents and reduces accumulation of settleable material.



Gas Pistons

Gas bubbles rise up tubes and act like pistons, pushing the sludge to surface. This confined gas mixing method generally has a low power requirement and is effective against scum buildup.

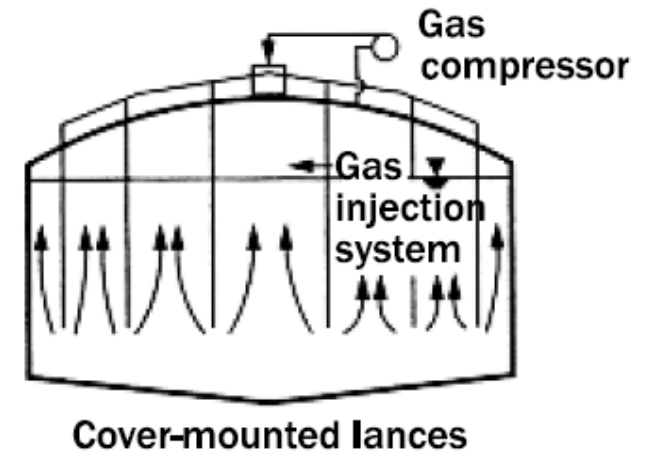
Gas recirculation



Unconfined Diffuser System

Gas is discharged continuously through diffusers. It is effective against solids deposits. However, it does not provide good top mixing, which results in scum buildup.

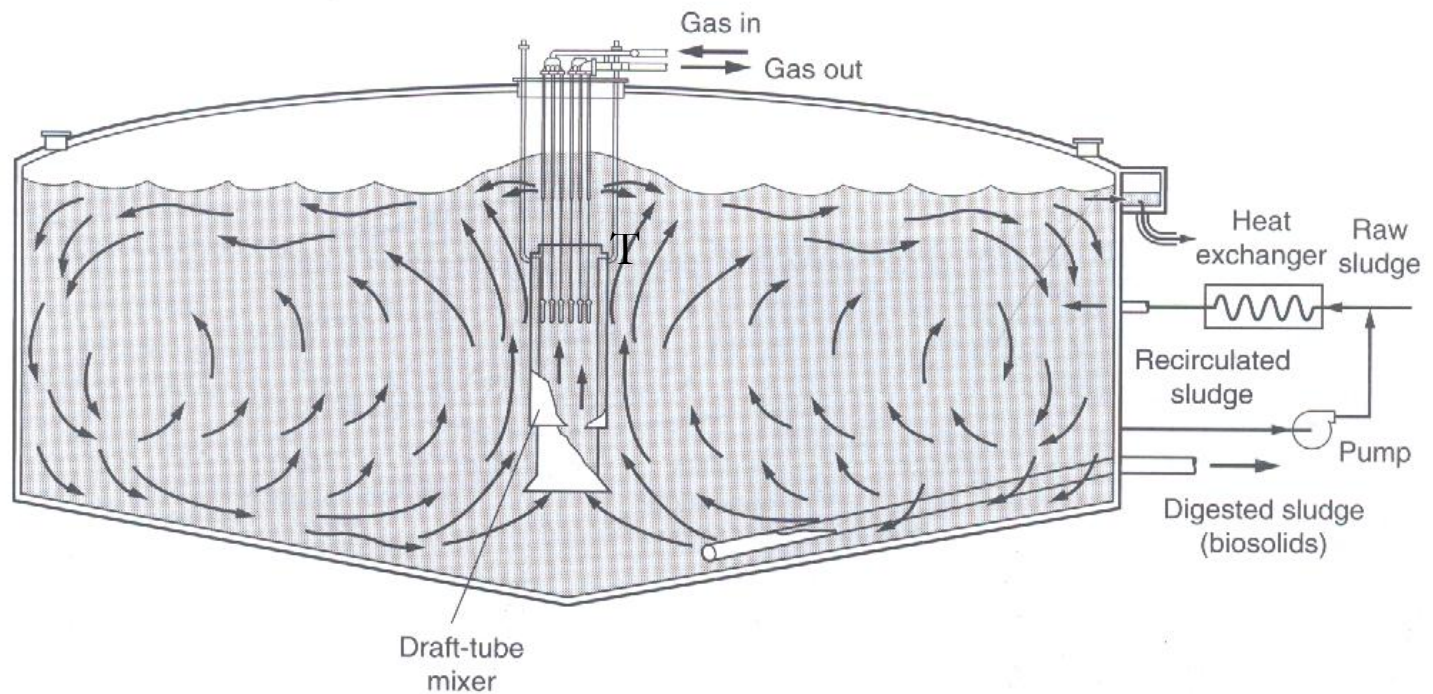
There is also a potential for diffuser clogging.



Unconfined Lance Gas Recirculation

Gas is discharged continuously through the injection pipes (lances) or sequentially by use of a rotary valve and preset timers. It is effective against scum buildup, however solids deposit problem due to the less efficient mix regime.

Gas recirculation



High-rate gas-mixed cylindrical digester

Mixing with pumping

- ❖ Externally mounted pumps withdraw sludge from tank and re-inject it through nozzles at the bottom of tank and near the surface to break up scum accumulation.
- ❖ Pumps are easier to maintain and provide better mixing control.
- ❖ Pumped recirculation also allows external heat exchangers for heating the digester and uniform blending of raw sludge with heated circulating sludge.
- ❖ Disadvantages include impeller wear from grit in the sludge, plugging of pumps by rags, and bearing failures.
- ❖ Axial or mixed flow or screw centrifugal pumps are used.

Heating

- ❖ Heating is essential because rate of microbial growth, and therefore rate of digestion and gas production increase with temperature.
- ❖ Most commonly, high-rate digestion operates in the mesophilic range 30 to 36°C.
- ❖ The contents of digester are heated and maintained consistently within 0.5°C of design temperature because especially methanogens are easily inhibited by even small changes in temperature.

Amount of heat required

$$H_1 = W_s \cdot C_p \cdot (T_2 - T_1)$$

H_1 : heat required to heat feed sludge (kg·cal/h)

W_s : mass rate of influent sludge (kg/h)

T_1 : temperature of feed sludge (°C)

T_2 : design operating temperature of digester (°C)

C_p : specific heat of feed sludge

(assumed to be same as water = 1 cal/°C)

Amount of heat required

$$H_2 = U \cdot A \cdot (T_2 - T_3)$$

H_2 : heat loss (kg·cal/h)

U : heat transfer coefficient (kg·cal/m²·s·°C)

A : surface area through which heat losses occur (m²)

T_2 : design operating temperature of digester feed sludge (°C)

T_3 : temperature of outside the digester (°C)

Heating

- ❖ Common insulating materials are glass wool, insulation board, urethane foam and dead air space.
- ❖ A facing is placed over the insulation for protection and to improve aesthetics.
- ❖ Common facing materials are brick and metal siding.
- ❖ Walls below ground level have different heat transfer properties depending on groundwater level and frost penetration.

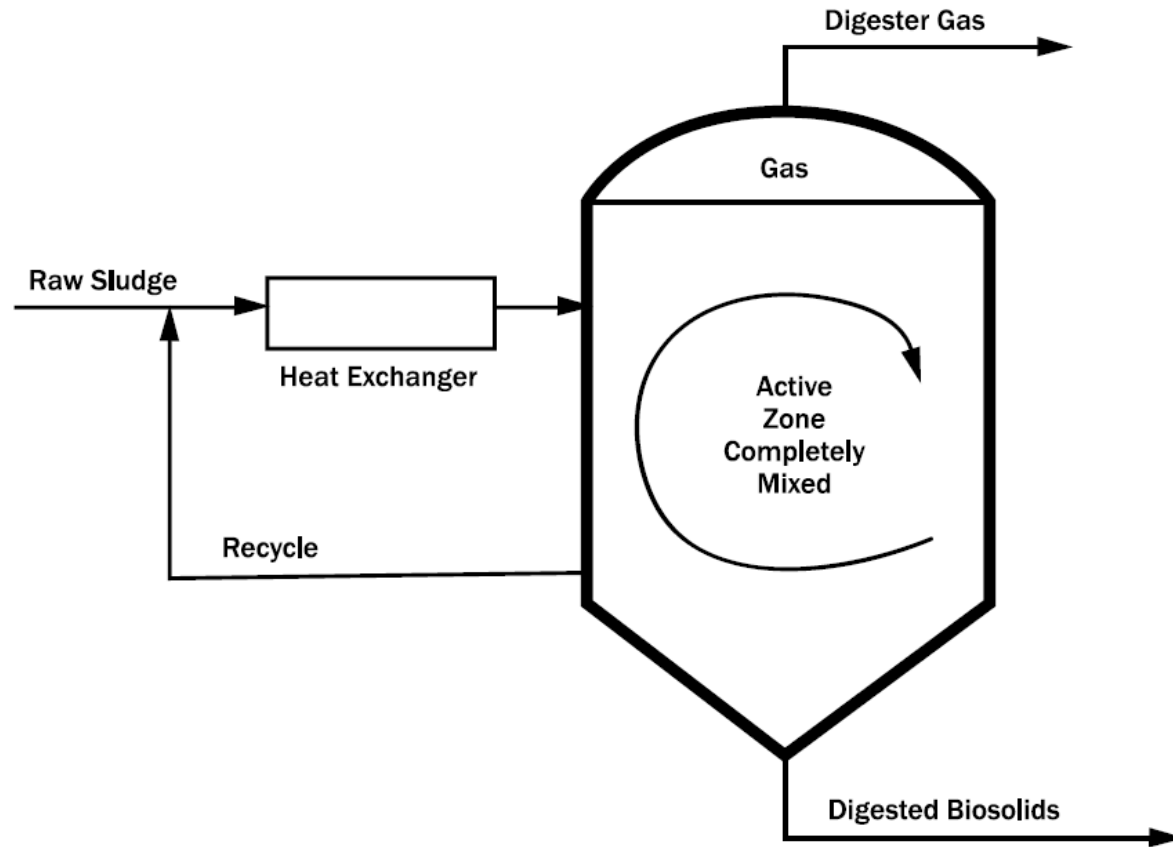
Heating equipment

- ❖ External heat exchangers are the most commonly used heating equipment because of their flexibility and ease of maintenance.
- ❖ Other heating methods are steam injection, direct flame heating by passing hot combustion gases through the sludge, and heat exchanger coils placed inside the tank
- ❖ These methods have been used in the past but have been discontinued because of the better heat transfer efficiency of the external heat exchangers.

Heating equipment

- ❖ An advantage of external heat exchangers is that recirculating digester sludge can be blended with raw sludge feed before heating in order to seed the raw sludge with anaerobic organisms.
- ❖ Cold sludge should never be added directly to the digester because the thermal shock will be detrimental to the anaerobic bacteria.
- ❖ Three types of external heat exchangers are commonly used: water bath, jacketed pipe, and spiral.

External heat exchangers

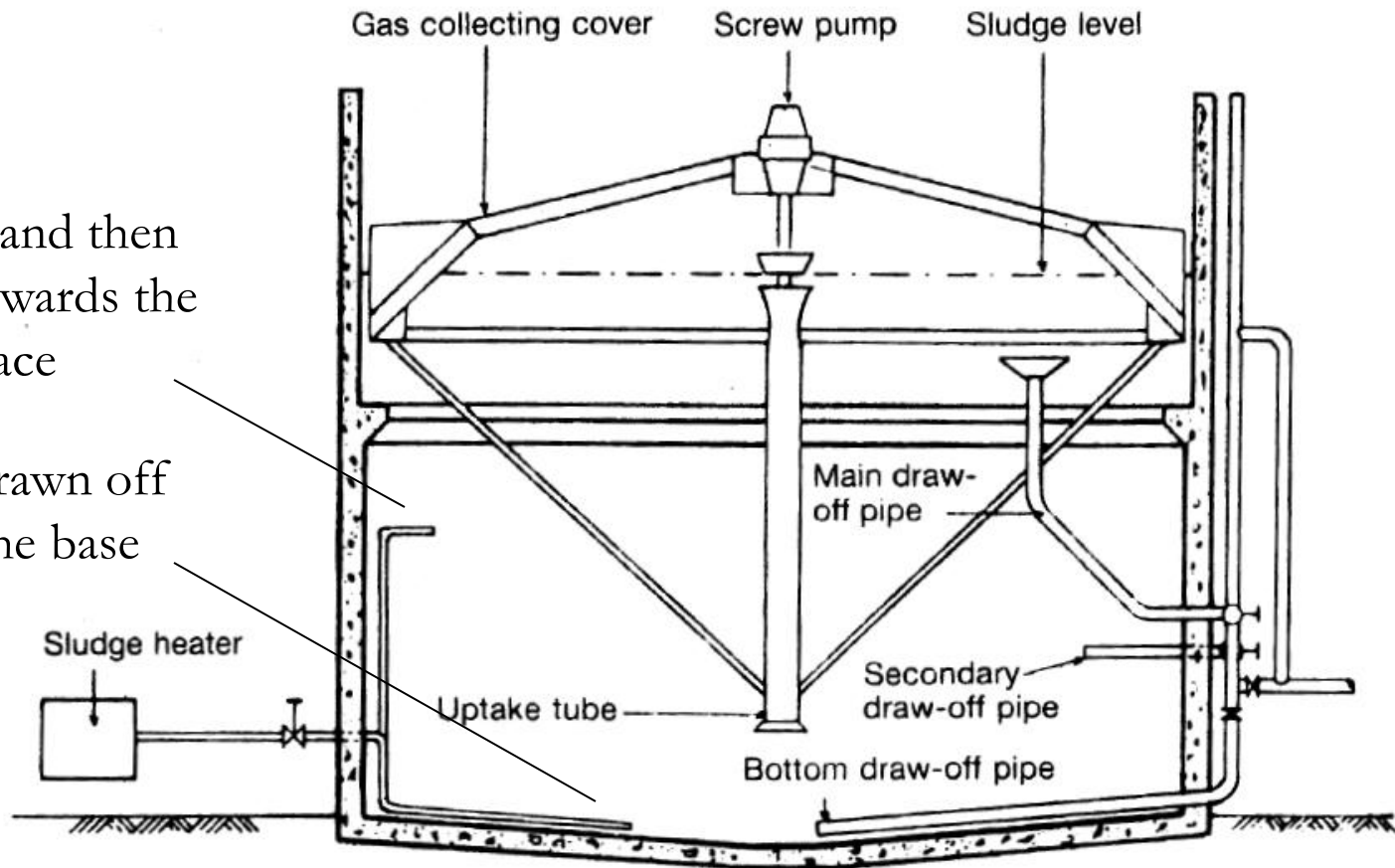


External heat exchangers

3. It is not immediately drawn up the central uptake tube, thus ensuring maximum utilization of heat

2. Heated and then returned towards the surface

1. Sludge is drawn off from near the base



Heat exchangers

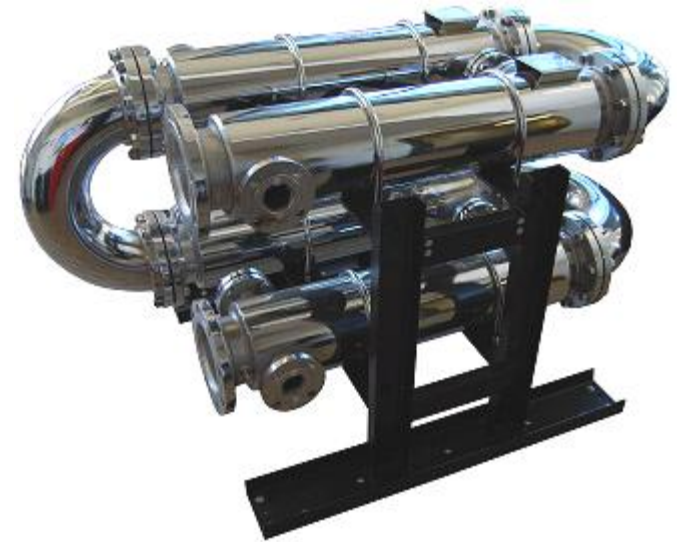
- ❖ In a water bath heat exchanger, boiler tubes and sludge piping are located in a common water-filled container.
- ❖ Hot water is pumped in and out of the bath to increase heat transfer.
- ❖ In a jacketed pipe heat exchanger, hot water is pumped countercurrent to the sludge flow through a concentric pipe surrounding the sludge pipe.
- ❖ Spiral heat exchanger is also a countercurrent flow design; however, the sludge and water passageways are cast in a spiral.

Heat exchangers

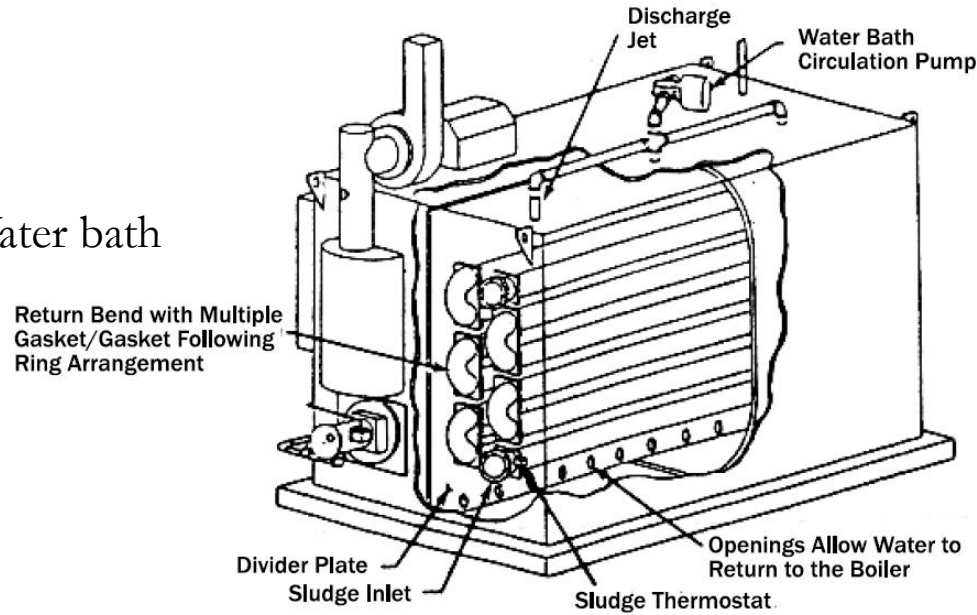
- ❖ Hot water used in a heat exchanger is most commonly generated in a boiler fueled by sludge gas.
- ❖ Provisions for burning an auxiliary fuel such as natural gas, propane, or fuel oil must be included to maintain heating during periods of low digester gas production or high heating demand, such as for digester startup.
- ❖ If a cogeneration system is used, waste heat from sludge gas–powered engines used to generate electricity or directly to drive pumps or blowers is sufficient to meet digester requirements.

Heat exchangers

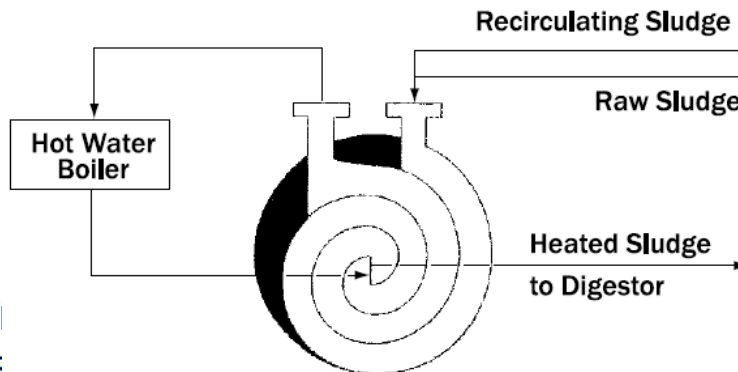
Jacketed pipe



Water bath



Spiral



Spiral



Digester performance

All process streams in an AD should be monitored for Q and analyzed for various constituents physical conditions.

- ❖ *Feed sludge*: TS, VS, pH, alkalinity, temperature
- ❖ *Digester content*: TS, VS, VFAs, alkalinity, temperature
- ❖ *Digested sludge draw-off*: same as digester content
- ❖ *Digester gas*: percentage of CH₄, CO₂ and H₂S
- ❖ *Heating fluid (hot water)*: TDS, pH
- ❖ *Supernatant*: pH, BOD, COD TS, total nitrogen, ammonia nitrogen, phosphorus