Sludge Management: Calculations

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Introduction

- The term '***sludge***' has been used to designate the solid by-products from wastewater treatment.
- In the biological treatment processes, part of the organic matter is absorbed and converted into microbial biomass, generically called biological or secondary sludge. This is mainly composed of biological solids, and for this reason it is also called a ***biosolid***.
- The utilization of this term still requires that the chemical and biological characteristics of the sludge are compatible with productive use, for example, in agriculture.
- The term '***biosolids***' is a way of emphasizing its beneficial aspects, giving more value to productive uses, in comparison with the mere non-productive final disposal by means of landfills or incineration.
- Although the sludge represents only 1% to 2% of the treated wastewater volume, its management is highly complex and has a cost usually ranging from 20% to 60% of the total operating costs of the wastewater treatment plant.
- Besides its economic importance, the final sludge destination is a complex operation, because it is frequently undertaken outside the boundaries of the treatment plant.

- The amount of sludge produced in wastewater treatment plants, and that should be directed to the sludge processing units, can be expressed in terms of mass (g of total solids per day, *dry basis*) and volume (m3 of sludge per day, *wet basis*).

Example

For a 100,000-inhabitant conventional activated sludge plant compute the amount of sludge in each stage of the sludge treatment.

	Sludge removed from the liquid phase	
Wastewater treatment system	Sludge mass (gSS/inhabitant·d)	Dry solids conc. (%)
Conventional activated sludge		
• Primary sludge	35–45	2–6
• Secondary sludge	25–35	0.6–1
• Mixed sludge	60–80	1–2

Solution:

Sludge removed from the activated sludge system, to be directed to the sludge treatment stage:

The activated sludge system produces primary and secondary sludge.
Sludge mass production:

- Primary sludge: 35 to 45 gSS/inhabitant·d
- Secondary sludge: 25 to 35 gSS/inhabitant·d
- Mixed sludge (total production): 60 to 80 gSS/inhabitant·d

….. Example

Sludge mass production:

- Primary sludge: 100,000 inhabitants × 40 gSS/inhabitant·d = 4,000,000 gSS/d = 4,000 kgSS/d
- Secondary sludge: 100,000 inhabitants × 30 gSS/inhabitant·d = 3,000,000 gSS/d = 3,000 kgSS/d
- Mixed sludge (production total): 4,000 + 3,000 = 7,000 kgSS/.d

Sludge volume production:

- Primary sludge: 100,000 inhabitants × 1.5 L/inhabitant·d = 150,000 L/d = 150 m^3/d
- Secondary sludge: 100,000 inhabitants × 4.5 L/inhabitant·d = 450,000 L/d = 450 m^3/d
- Mixed sludge (production total): 150 + 450 = 600 m^3/d

Design data

Density, specific gravity, VS/TS ratio and percentage of dry solids for various sludge types

Types of sludge	VS/TS Ratio	% dry solids	Specific gravity of solids	Specific gravity of sludge	Density of sludge (kg/m^3)
Primary sludge	0.75–0.80	2–6	1.14–1.18	1.003–1.01	1003–1010
Secondary anaerobic sludge	0.55–0.60	3–6	1.32–1.37	1.01–1.02	1010–1020
Secondary aerobic sludge (conv. AS)	0.75–0.80	0.6–1.0	1.14–1.18	1.001	1001
Secondary aerobic sludge (ext. aer.)	0.65–0.70	0.8–1.2	1.22–1.27	1.002	1002
Stabilisation pond sludge	0.35–0.55	5–20	1.37–1.64	1.02–1.07	1020–1070
Primary thickened sludge	0.75–0.80	4–8	1.14–1.18	1.006–1.01	1006–1010
Second thickened sludge (conv. AS)	0.75–0.80	2–7	1.14–1.18	1.003–1.01	1003–1010
Second thickened sludge (ext. aer.)	0.65–0.70	2–6	1.22–1.27	1.004–1.01	1004–1010
Thickened mixed sludge	0.75–0.80	3–8	1.14–1.18	1.004–1.01	1004–1010
Digested mixed sludge	0.60–0.65	3–6	1.27–1.32	1.007–1.02	1007–1020
Dewatered sludge	0.60–0.65	20–40	1.27–1.32	1.05–1.1	1050–1100

Anaerobic digestion

- The word ***digestion*** in wastewater treatment is applied to the stabilization of the organic matter through the action of bacteria in contact with the sludge, in conditions that are favorable for their growth and reproduction.

- The anaerobic digestion process, characterized by the stabilization of organic matter in an oxygen-free environment, has been known by sanitary engineers since the late 19th century.

Comparison between raw sludge and anaerobically digested sludge

Raw sludge	Digested sludge
Unstable organic matter	Stabilised organic matter
High biodegradable fraction in organic matter	Low fraction of biodegradable organic matter
High potential for generation of odours	Low potential for generation of odours
High concentration of pathogens	Concentration of pathogens lower than in raw sludge

- It is desirable to have solids concentrations in the raw sludge fed to digestion in the order of 4% to 8%. Higher solids concentrations can be used, as long as the feeding and mixing units are able to handle the solids increase. Solids concentrations lower than 2.5% are not recommended, as excess water has a negative effect on the digestion process.

- Anaerobic bacteria are sensitive to several substances that, depending upon their concentrations, are capable to completely stop the digestion process. The main inhibiting agents are hydrocarbons, organochlorinated compounds, non-biodegradable anionic detergent, oxidizing agents and inorganic cations.

- In a conventional activated sludge WWTP, mixed primary sludge and excess activated sludge are biologically stabilized under anaerobic conditions and converted into methane (CH_4) and carbon dioxide (CO_2).

- The process is accomplished in closed biological reactors known as anaerobic sludge digesters. Digester tanks are fed with sludge either continuously or in batches, and the sludge is kept inside the tank for a certain period of time previously determined during the design phase.

- The sludge and the solids have the same detention time in the digester.

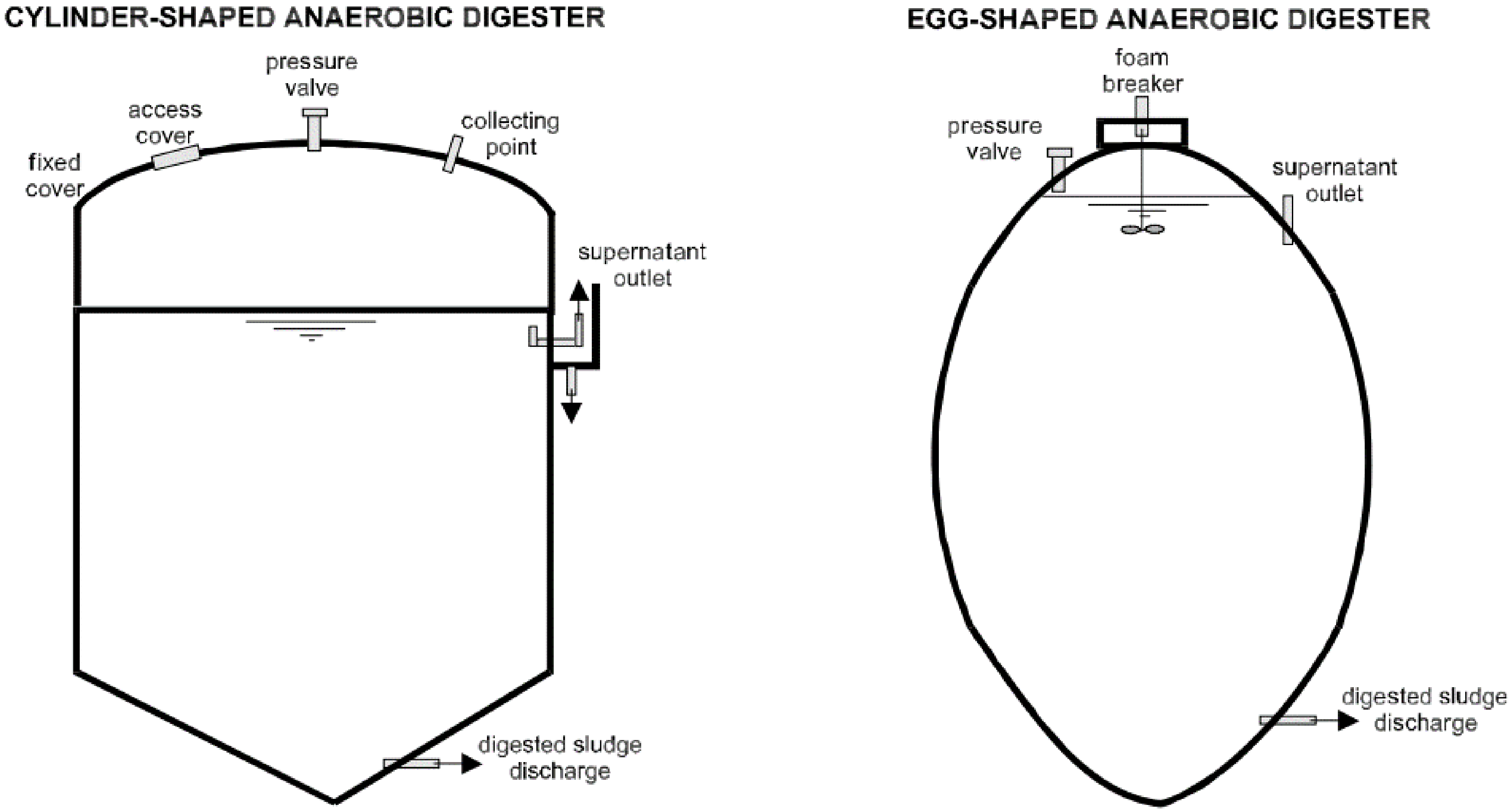
Design of anaerobic digesters

Typical design parameters for anaerobic sludge digesters

Parameters	Typical values
Detention time (θ_c) (d)	18–25
Volumetric organic load (kgVS/m^3·d)	0.8–1,6
Total solids volumetric load (kgSS/m^3·d)	1.0–2.0
Influent raw sludge solids concentration (%)	3–8
Volatile solids fraction in raw sludge (%)	70–80
Efficiency in total solids reduction (% TS)	30–35
Efficiency in volatile solids reduction (% VS)	40–55
Gas production (m^3/kgVS destroyed)	0.8–1.1
Calorific value of gas (MJ/m^3)	23.3
Digested sludge production (gTS/inhabitant·day)	38–50
Gas production (L/inhabitant·day)	20–30
Raw sludge heating power (MJ/kgTS)	15–25
Digested sludge heating power (MJ/kgTS)	8–15

Source: Adapted from CIWEM (1996)

Typical formats of anaerobic digesters (adapted from WEF, 1996)



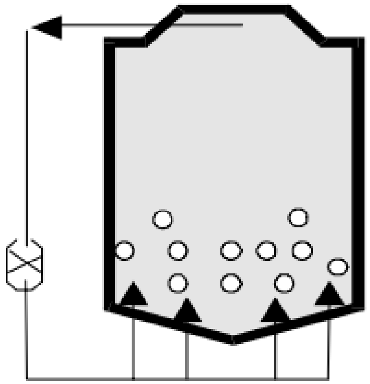
Design of anaerobic digesters

- Most cylinder-shaped sludge digesters have less than 25 m diameter.
- Traditional design has a height-to-diameter ratio ranging from 1:2 to 1:3, and up to 33% bottom slopes.
- Nowadays, anaerobic digesters are also being designed with a 1:1 height:diameter ratio and a small or even zero floor slope.
- Until the 1970s, the anaerobic digesters were designed for 25–30 day detention time to counterbalance possible volume losses due to sand accumulation, high water content of the raw sludge and deficiency of the mixing system.
- Nowadays, there is a trend to reduce the detention time to 18–25 days in warm-climate regions.
- The required volume for the sludge digesters is given by:

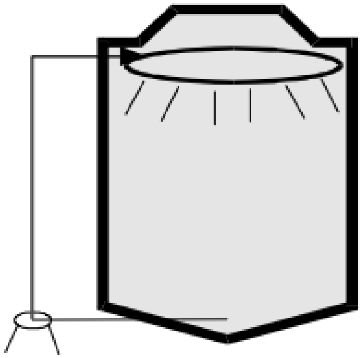
$$V = \frac{\text{Influent VS load (kgVS/d)}}{\text{Volumetric organic loading (kgVS/m}^3\text{·d)}}$$

Mixing in anaerobic sludge digesters

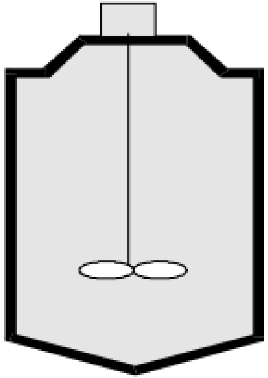
- The maintenance of a homogeneous sludge medium within the digester is a fundamental requirement for its good performance.
- Keeping homogeneity is assured through sludge mixing devices, aiming to:
  - ✓ assure the internal medium uniformity from the physical, chemical and biological points of view,
  - ✓ quickly disperse the raw sludge when it enters the tank,
  - ✓ minimize thermal stratification, avoiding temperature gradients,
  - ✓ minimize foam formation and inert material (mainly sand) accumulation,
  - ✓ maximize the useful volume of the digester, minimizing hydraulic short circuits and the occurrence of dead zones,
  - ✓ dilute the concentration of occasional inhibiting agents throughout the digester volume



(a) Mixing through recirculation of pressurised biogas

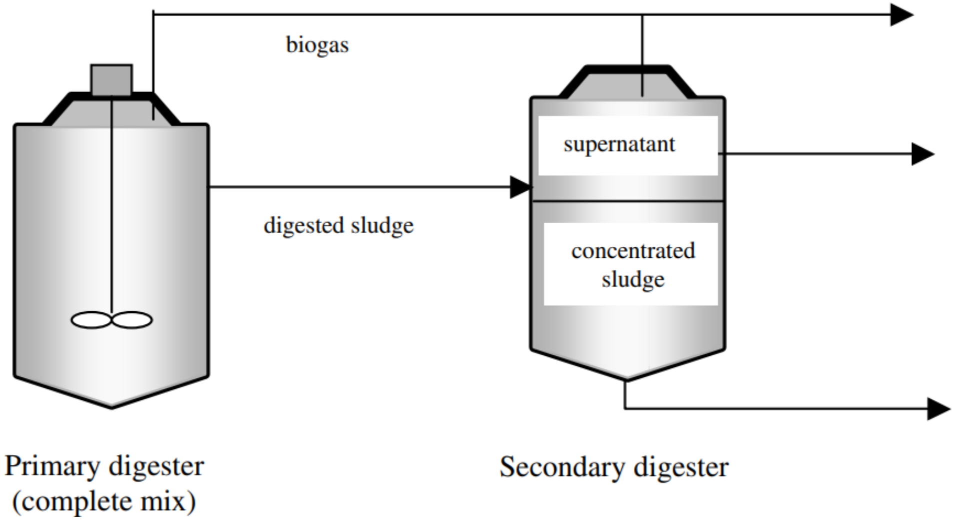


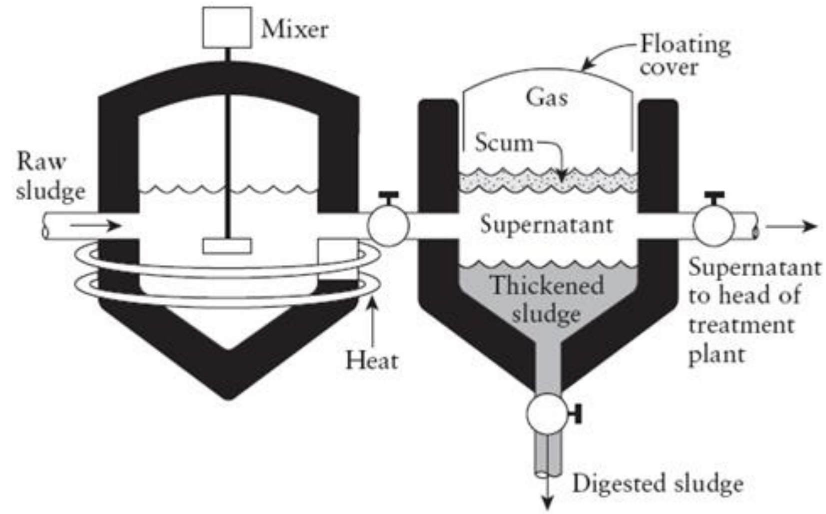
(b) Mixing through pumped recirculation of sludge



(c) Mixing through mechanical mixer

Two-stage anaerobic sludge digestion system





- ***The primary digester*** is a complete-mix reactor responsible for fast stabilization of the organic matter,

- In ***the secondary digester*** the separation of solid/liquid phases prevails. Secondary digesters usually do not have mixing or heating systems, except when designed to replace the primary digester during maintenance periods.

Biogas

- Anaerobic digestion processes produce biogas, which is basically a mixture of methane (CH_4), carbon dioxide (CO_2), small concentrations of nitrogen, oxygen, hydrogen sulphide (H_2S) and traces of volatile hydrocarbons.
- Biogas production in anaerobic digesters is directly associated with the raw sludge feeding. Maximum biogas production in anaerobic digesters fed at regular intervals along the day normally occurs 2 hours after each feeding.
- The production rate of biogas may be estimated as 0.8 m^3/kg volatile solids destroyed, which is equivalent to approximately 25 L/inhabitant·day.
- Biogas density and thermal capacity vary with the composition. The higher the methane concentration in the biogas, the higher its heating value and the lower its density.
- A 70%-methane biogas has a heating power of approximately 23,380 kJ/m^3 (6.5 kW/m^3).
- As a simple comparison, natural gas, which is a mixture of methane, propane and butane, has a heating power of 37,300 kJ/m^3 (10.4 kW/m^3).

Poor mixture for combustion	Inflammable mixture	Mixture too rich for combustion

LEL = 5% UEL = 15%

The main characteristics of the biogas components

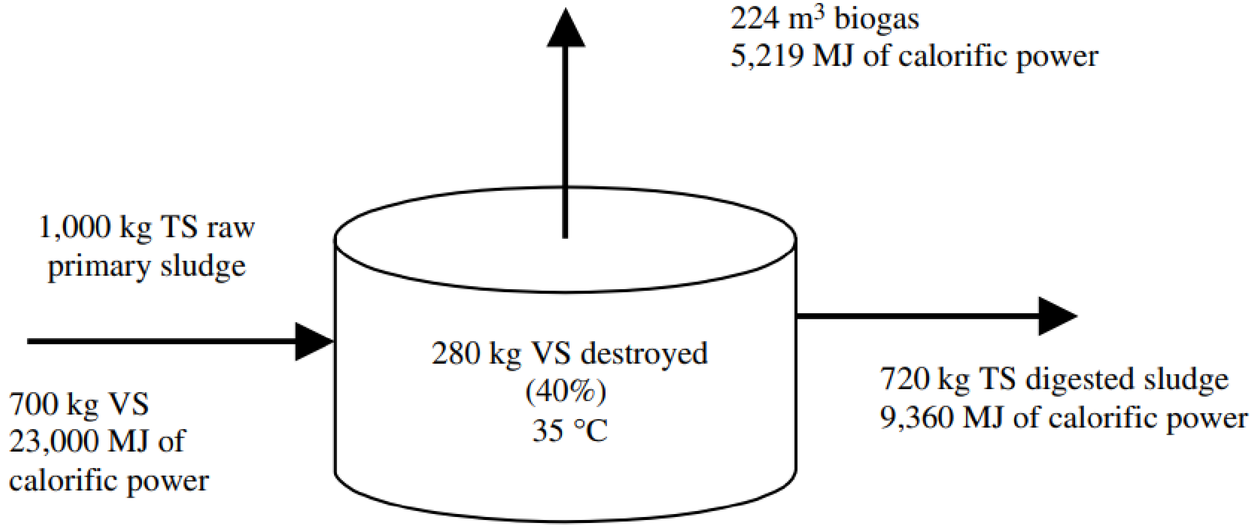
- Methane (CH_4) – odorless, colorless and inflammable (explosive limit) between 5% LEL and 15% UEL. The relative density (0.55) is lower than air, being easily dispersed. It is not toxic, although at very high concentrations may reduce the air oxygen concentrations to asphyxiating levels.

- Carbon dioxide gas (CO_2) – odorless, colorless and non-inflammable. The relative density (1.53) is higher than air, being asphyxiating at concentrations above 2%.

- Hydrogen sulphide (H_2S) – colorless, inflammable and with a characteristic rotten-egg smell. It has a relative density (1.19) nearly equal to air and 4.3% LEL and 43.5% UEL. It is irritant and asphyxiating. Concentrations higher than 1% leads to unconsciousness.

Gas	% (volume/volume)
Methane	62–70
Carbon dioxide	30–38
Hydrogen sulphide	50–3,000 ppm
Nitrogen	0.05–1.0
Oxygen	0.022
Hydrogen	<0.01
Water vapour	Saturation

Typical mass and heat balance of anaerobic sludge digestion



- *raw sludge heating power: 23 MJ/kgTS × 1,000 kgTS = 23,000 MJ*
- *amount of volatile solids destroyed: 700 kgTS × 0.4 = 280 kg VS*
- *amount of digested sludge: 1000 – 280 = 720 kgTS*
- *digested sludge heating power: 13 MJ/kgTS × 720 kgTS = 9,360 MJ*
- *biogas production: 0.8 m^3/kg VS destroyed*
- *biogas volume produced: 280 kgVS × 0.8 = 224 m^3*
- *biogas heating power: 23.3 MJ/m^3 × 224 m^3 = 5,219 MJ*

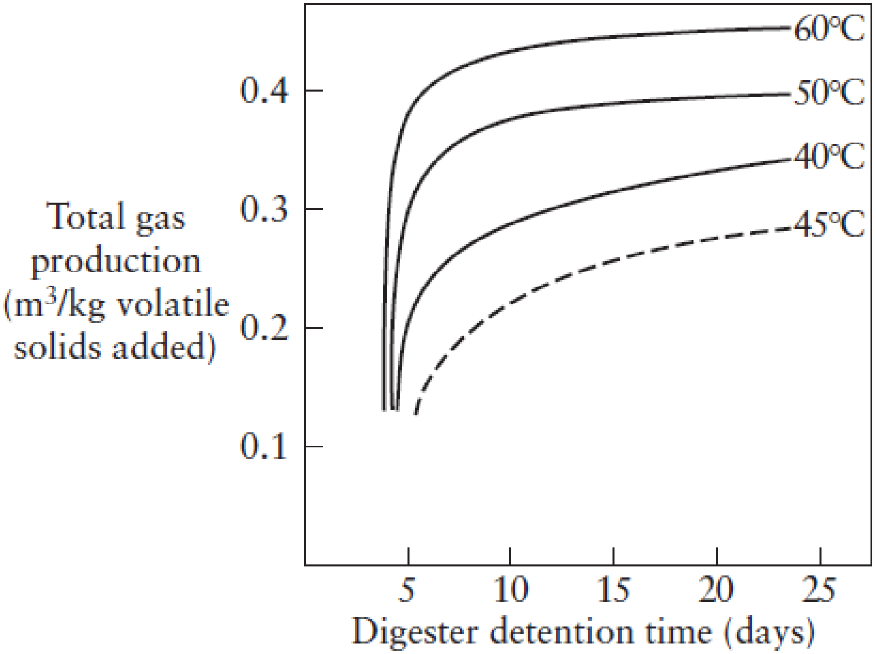
- The raw sludge heating power ranges from 11 to 23 MJ/kgTS on a dry weight basis, depending upon the type of sludge and the concentration of volatile solids.
- The digested sludge has a lower heating power, which ranges from 6 to 13 MJ/kgTS due to the smaller concentration of volatile solids.
- Heating is necessary in cold weather climates to compensate for heat losses through the digesters outer surface and to raise the temperature of the raw sludge fed daily.
- Biogas can be used as a heat source for digester heating.
- Biogas is used to feed the furnace and heat the boiler, with the sludge heating indirectly accomplished by heat exchange units.
- In most cases, the system is self-sufficient and no further complementary external heating source is required, except during winter in very cold regions.
- An external heating source (e.g., fuel oil) is necessary only for the unit start-up.

Needed heat

- The heat needed to keep anaerobic digesters near 35 ◦C – mesophilic digestion – is the heat needed to heat the incoming raw sludge plus the heat needed to compensate for heat losses through the digesters walls, cover and bottom.

- Thus:

$$Q = M_f \times C_p \times \Delta T_1 + H$$



where:

Q = sludge digester daily energy demand (kJ/d)
M_f = raw sludge mass fed to the digester (kg/d)
C_p = specific heat of water (kJ/kg·°C)
ΔT_1 = difference between the raw sludge temperature and the digester temperature (°C)
H = heat loss through the digester walls (kJ/d)

- The daily heat loss through all the digester surface can be determined by:

$$H = U \times A \times \Delta T_2 \times 86.4$$

where:

U = heat transfer coefficient ($J/s{\cdot}m^2{\cdot}{}^\circ C$)

A = digester outer surface area (m^2)

ΔT_2 = difference between the digester inner temperature and the outer temperature (°C).

- Raw sludge mass fed to digester – Mf: thermodynamically, a raw sludge up to 6% solids content may be considered water, with a density of 1 kg/L and specific heat (Cp) of 4.20 kJ/kg·◦C.
- Temperature difference – ΔT: varies with the site climatic conditions. Inner digester temperature must remain between 35◦C ± 3◦C to assure mesophilic digestion conditions.
- Heat transfer coefficient – U: depends on the material used to build the digester tank. Literature gives U values of 2–3 J/s·m^2.◦C for well-insulated digesters, whereas poorly insulated digesters may have U values of 3–5 J/s.m^2.◦C.
- Digester surface area – A: includes side walls, cover and bottom area of digester tank.

HW

Design a primary anaerobic digester using data.

Input data:

- Population: 67,000 inhabitants
- Average influent flow: Q = 9,820 m^3/d
- Influent SS load: 3,720 kg/d
- Influent SS concentration: SS = 379 mg/L
- SS removal efficiency in the primary clarifier: 60% (assumed
- Mixed sludge load to digester: 3,307 kgTS/d
- Influent sludge flow: Q = 64.2 m^3/d
- VS/TS ratio = 0.77

Requirements:

(a) Digester volume
(b) Hydraulic detention time
(c) Primary digester effluent sludge (influent sludge to secondary digester)
(d) Heat balance in digester