Design and development of an anaerobic bio-digester for application in sewage sludge digestion for biogas and bio-solids generation using Acti-zyme as bio-catalyst

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Abstract

Anaerobic digestion for biogas production is vital in sewage sludge management. This paper focuses on the design and development of an anaerobic bio-digester that can be utilized for biogas production utilizing Acti-zyme as the digestion bio-catalyst from sewage sludge. A stainless steel lab scale bio-digester with a capacity of 390 L/day and an operating efficiency of 75% was considered. The bio-digester allowed for addition of both the Acti-zyme and sewage sludge, the removal of the biogas and bio-solids generated during the digestion process. Process and equipment safety was ensured by maintaining the temperature at 35°C, pressure at 1 atmosphere as well as ensuring the flow of the substrate was maintained at 75% to minimize as operational hazards. Agitation was maintained at 60 rpm for uniform mixing whilst pH was maintained at 7 for enhancing Acti-zyme activity. The anaerobic bio-digester can either be up scaled or downscaled for application in sewage sludge management using Acti-zyme.

Keywords: Acti-zyme, anaerobic bio-digester design, biogas, sewage sludge digestion, bio-solids

1. Introduction

Sewage sludge accumulation problems are increasing in developing countries sewage treatment plants resulting in environmental problems hence alternative uses need to be found [1]. This has led for alternative uses of sewage sludge to biogas to be adopted especially anaerobic sewage sludge digestion to biogas [2]. Biogas is a combination of bio-methane, carbon dioxide, hydrogen sulfide and ammonia gases produced from reaction of substrates which undergo enzymatic size reduction followed by hydrolysis, acidogenesis and methanogenesis respectively with the aid of methanogenic bacteria that supports the production of biogas [3-5]. Recently Acti-zyme, a bio-catalyst, has been used in sewage treatment for bio-nutrient removal [6-7] and in sewage sludge digestion to produce a high quality bio-methane and bio-solids [8-9]. However, the bio-digesters that can be used and be adopted for sewage sludge digestion with Acti-zyme being employed as bio-catalyst are still yet to be developed. Acti-zyme as a bio-catalyst employed in sewage sludge digestion thrives best in anaerobic conditions hindering H_2S and ammonia production [8-9]. This work led to the development of anaerobic bio-digester that can be applied for biogas generation from sewage sludge using Acti-zyme as bio-catalyst.

2. Materials and methods

A bio-digester for treating 390 L/day of sewage sludge per day was designed and fabricated. An operating efficiency of 75% was considered for the bio-digester design. Acti-zyme used in the test runs was obtained from AusTech in Australia. Sewage sludge was obtained from a local sewage treatment plant.

3. Bio-digester design considerations

3.1 Overall mass balance on the bio-digester

An overall mass balance based on Equation 1 and Figure 1 was considered for processing 290 L/day (75% 0f total capacity) of sewage sludge from the lab scale bio-digester resulting in an overall biogas conversion of around 78% when utilizing Acti-zyme loading of 50 g/m^3 (0.095 L/day for the designed bio-digester) as the optimum loading [7-8]. The amount of bio-solids generated was considered to be around 1% after removal of moisture based on previous experimental work done on the techno-economic feasibility of biogas production using Acti-zyme as bio-catalyst [9].

$$Sewage\ sludge + Acti - zyme \ \rightarrow Biogas + Bio - solids \ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

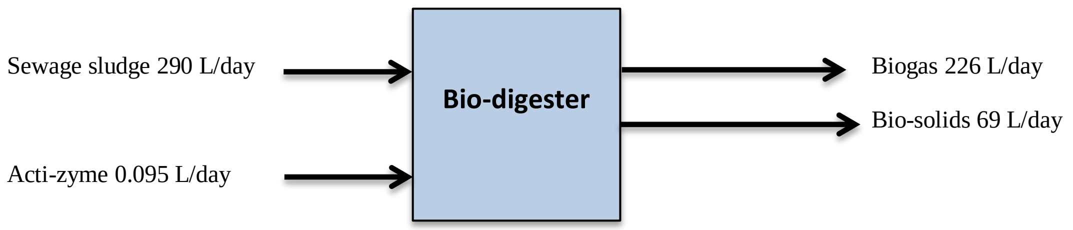

Figure 1: Overall mass balance around the bio-digester used for sewage sludge to biogas

3.2 Design considerations

The design and construction of the bio-digester prevented foreign contamination. Optimal mixing with low, uniform shear must be achieved by proper designing of the agitator. Adequate mass transfer must be achieved by monitoring the speed of agitator. Furthermore, clearly defined flow conditions that can be maintained by proper process control through adequate valves and monitoring devices. Feeding of sewage sludge with prevention of under or overdosing by proper feed ports and monitoring must be ensured. Suspension of the Acti-zyme throughout the sewage sludge must be maintained with gentle mixing at 60 rpm. Compliance with design requirements such as ability to be cleaned, simple construction, simple measuring, and control, regulating techniques, scale-up, flexibility; long term stability and compatibility with the up and downstream processes were ensured. The bio-digester consisted of Rushton turbine impellers for agitation and a jacket around it for cooling purposes and ensuring the temperature was maintained at 37 °C. Sewage sludge was added at 7.5 g/L. day [8] and Acti-zyme was added at 50 g/m^3 [5] in the bio-digester and digestion was allowed to occur for up to 40 days. According to previous studies, the conversion of sewage sludge to biogas utilizing Acti-zyme is 78 % and for that conversion the reaction time is 40 days [8].

3.2.1 Components of bio-digester

Basic components of the bio-digester included the drive motor, heaters, electric pump, vessel and accessories, peripheral equipment for biogas collection and instrumentation and sensors

3.2.2 Body construction

The vessel did not have any vessel used any corners to avoid dead zones and ensure all contact with the Acti-zyme and sewage sludge. In addition, smooth surfaces are essential for the same purpose.

3.2.3 Material of construction

Heat resistant stainless steel was used as vessel construction material. Side plates had lower thickness than top and bottom plates. Top and bottom plate were hemispherical to withstand pressures.

3.2.4 Sealing

Sealing between top plate and vessel was an important criterion to maintain airtight conditions since the process is anaerobic as well as to ensure containment of the bio-digester contents. This sealing ensured a tight joint in spite of expansion of vessel material during the anaerobic process. This was achieved by the use of simple O ring type seals or double sealing with steam between two seals. The materials used for sealing was butyl rubbers. The seals should be changed after finite time for maintaining of the anaerobic conditions.

3.2.5 Safety valve

Safety valves are necessary for pressure release when pressure is increased. This is done through a spindle lifted from its seating against the pressure to release pressure or through rupturing of discs to release pressure. In case of releasing the biogas, the escaping biogas must be treated before release due to the traces of H_2S available.

3.2.6 Baffles

Baffles are metal strips that prevent vortex formation around the walls of the bio-digester. These metal strips attached radially to the wall for every $1/10^{th}$ of vessel diameter. Four baffles were used. There should be enough gaps between wall and baffle so that scouring action around vessel is facilitated. This movement minimizes Acti-zyme accumulation on baffles and walls. Cooling coils were also attached to the battles for maintaining the temperature at 35°C since the methanogenesis process is an exothermic process.

3.2.7 Shape of bio-digester

A cylindrical shape was the appropriate one to use because the cylindrical shape encourages the sewage sludge and Acti-zyme to rotate within the bio-digester and assist to achieve perfect mixing of the sewage sludge and Acti-zyme.

3.2.8 Batch time

In sizing of a bio-digester, Equation 2 has to be followed to calculate the reaction time;

$$-In\,(1 - X_A) = kt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .2$$

Whereby X_A is the concentration of the sewage sludge in the bio-digester and k is the digestion rate constant and t is the time required for the biogas to be produced from sewage sludge utilizing Acti-zyme. According to experimental work done for on biogas conversion from sewage sludge and Acti-zyme for a conversion of 78%, the time taken for the batch reaction is 40 days [7-8]. This was done in consideration of the lag phase, exponential phase, deceleration phase and stationery phases during biogas production on the sewage sludge. Equation 3 is a representation of how the total batch time was calculated.

$$T_T = T_L + T_E + T_D + T_S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Whereby T_L is the time required for the lag phase, T_E is the time taken for the exponential phase, T_D is the time taken for the deceleration phase, T_S is the time taken for the stationery phase and T_T is the time taken for the entire batch process. The 40 days retention time for the entire batch operation is indicated in Figure 1 for both a system with Acti-zyme (A_1) and another without Acti-zyme (A_o).

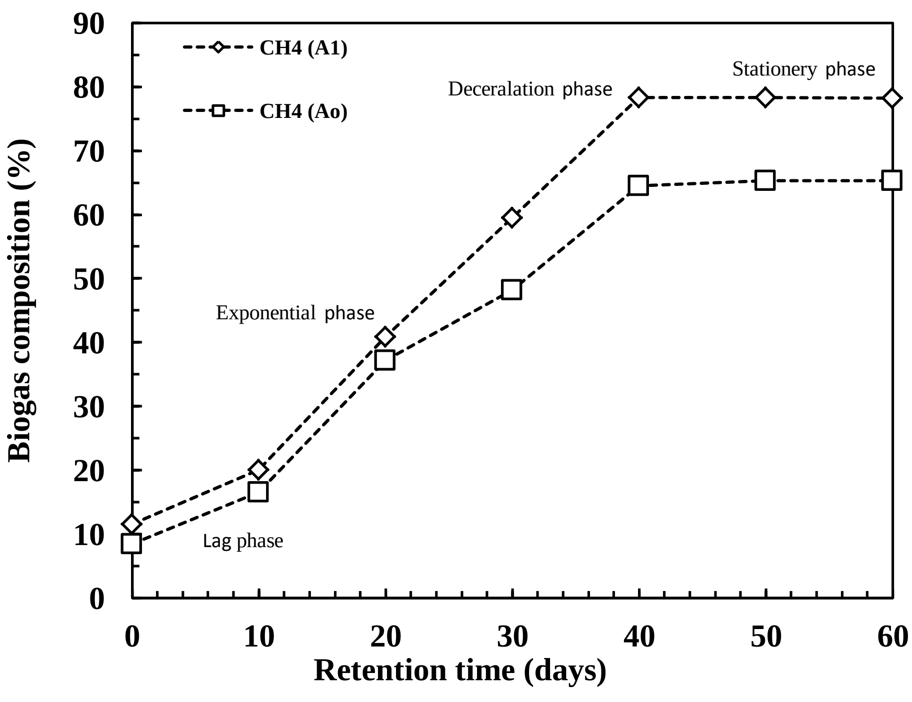

Figure 1: Various retention time stages in the bio-digester during sewage sludge digestion

3.2.10 Geometric considerations

The bio-digester had the following dimension: height (H) to diameter (D) ratio of 4 (H/D = 4), baffle width (J) to bio-digester diameter of 1/12 (J/D = 1/12), agitator diameter (D_i) to bio-digester diameter was 1/3 (D_i/D = 1/3), distance between the bottom of the bio-digester and the turbine impeller diameter (E) to the diameter of the bio-digester was 1/3 (E/D = 1/3), the Rushton turbine width (W) to the Rushton turbines diameter was 1/5 (W/D_i = 1/5) and the Rushton turbine length (L) to the Rushton turbines diameter was 1/4 (L/D_i = 1/4). The geometric representation is shown in Figure 2.

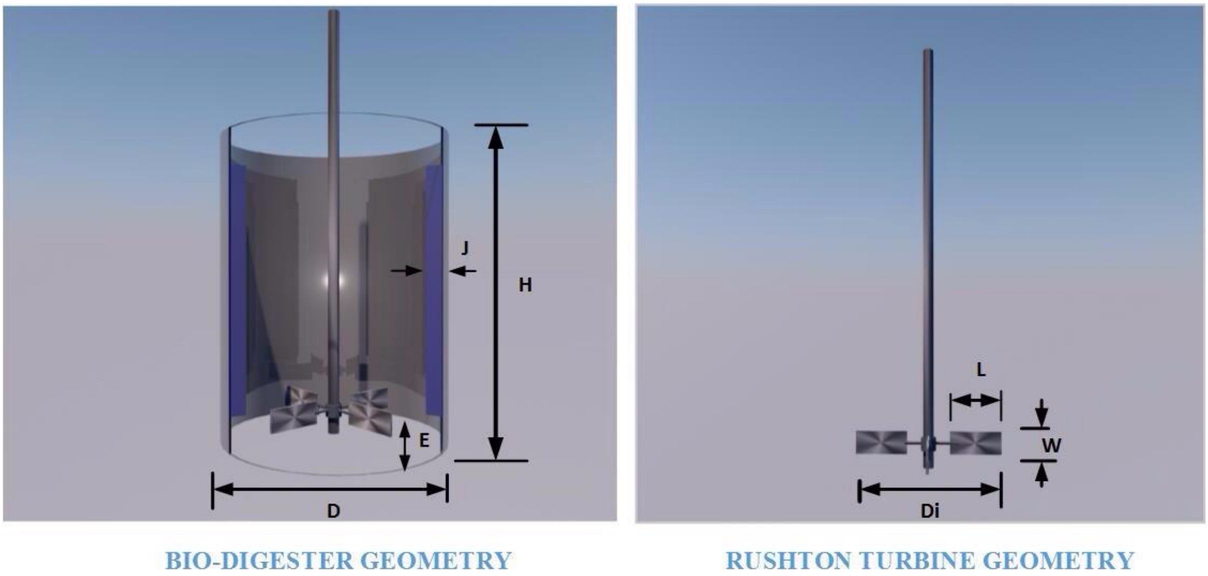

Figure 2: Bio-digester design considerations

A bio-digester that then processed 390 L/day with a working volume of 75% was fabricated and used for biogas and bio-solids generation from sewage sludge utilizing Acti-zyme. The fabricated bio-digester is indicated in Figure 3.

Figure 3: Prototype of the designed bio-digester

A summary of the batch type bio-digester design considerations is given in Table 1.

Table 1: Summary of the bio-digester design parameters

Parameter	**Value**
Volume	0.39 m^3 (390 L)
Height	2 m
Diameter	0.5 m
Temperature	35 ^oC
Working pressure	1 atmos
Retention time	40 days
Height to diameter ratio	4
Type of head	Hemispherical
Depth of dished bottom	0.125 m
Wall thickness	0.019 m
Head thickness	0.021 m
No. of baffles	4
Width of Baffle	0.042 m
Height of Baffle	1.5 m
Power per unit volume	1.3
Sewage sludge loading	290 L/day
Acti-zyme loading	0.0195 L/day

3.2.11 Process control

The process parameters such as temperature and pressure were controlled during biogas production to ensure safety operating conditions and to maintain maximum productivity hence profits. In a biogas production plant, explosive may arise from clouds of dust, carbon monoxide and methane hence good ventilation can prevent accumulations of bio-methane in sludge storage tanks.

Control and monitoring bio-digester system

The integral part of a high-quality bio-digester is a process controller. Such a controller is commonly specially formed for a definite bio-digester brand. This is rather connected with the fact that the Acti-zyme growth processes have relatively high requirements in respect to precision and sophistication. All this is despite the fact that almost all bio-digesters monitor and regulate the same values actually invariably.

Temperature

Heat is generated from any anaerobic process due to microbial activity. The heat control in the bio-digester was aided by inter coils and cold water circulation. Components used for controlling temperature in a bio-digester were a water inlet, pressure regulator, magnetic inlet valve, heater, circulation pump, jacket, cooling water valve, cold finger, pt-100 sensor, controller, exit gas cooler and drain to remove overflow. The thermocouple measures the temperature of the water in flowing in the bio-digester jacket and sends the value to the comparator. The comparator compares the set point (35 ^{0}C) temperature with the measured and sends the error detected to the controller. The controller sends a signal to the final controller element which will take the appropriate corrective.

Sewage sludge flow rate

A slurry pump which is ideal for low flow rates is useful in case of batch systems for controlling the flow rate of the sewage sludge of 290 L/day. Regulated piston movement in the pump controls the flow rate by squeezing and releasing pulse flow.

Pressure measuring and controlling device

The bourbon tube pressure gauge was used to measure any pressure changes from the 1 atmosphere. This is a partial coil which has an elliptical cross section which becomes circular with increasing pressure and the motion straightens out the coil. The process pressure is fixed to one end of coil and other end fixed to geared sector and pinion movement which actuates an indicator pointer. The pointer moves on a calibrated meter which is used to indicate the pressure.

pH monitoring device

In for biological processes, it is important to have an accurate and precise measurement of pH. Mesophilic conditions favor pH of around 7 which promote bio-methane production hence this pH must be maintained. The sensing electrode consisting of a thin hydrogen permeable membrane containing a solution and an electrode was used. The membrane of the sensing electrode allows hydrogen ions to slowly pass, creating a positive voltage across the membrane. The voltage created in this electrode is then compared to the voltage in the reference electrode.

3.2.12 Hazard operability analysis

The hazard operability analysis (HAZOP) was done to foresee and predict the possible dangers, risks and harms so that they can be mitigated, control or eliminated to ensure a health and safe working environment without hazards. The HAZOP analysis for the bio-digester is indicated in Table 2. Potential hazards were identified and attributed to the feeding of the sewage sludge and Acti-zyme, agitation, temperature and pressure that may affect the operation of the bio-digester. In addition, the pH was be maintained at neutral pH so that Acti-zyme maintains its activity else if it becomes acidic or caustic, Acti-zyme will be denatured and hence no optimal biogas production will occur. The same applies not to Acti-zyme only but also to the methanogens that aid in the methanogenesis process.

Table 2: HAZOP for bio-digester

Guide word	Parameter	Deviation	Possible cause	Consequences	Corrective measures
Less	Temperature	Temperature < 35°C	Heating steam inlet valve fails it is closed	Low digestion rate hence low biogas yield Inefficient reaction of Acti-zyme Production of high quantities of bio-solids	Install temperature sensors (thermocouples, thermometers) to detect changes in temperatures Repair of the valve Valves should be checked regularly
More	Temperature	Temperature > 35°C	Heating steam inlet valve fails, it is fails to close	Excess of temperature have an effect on product quality Acti-zyme activity are deactivated Mesophillic conditions deactivated, lower biogas yield	Install temperature sensors such as thermocouple, thermometer
NO	Flow	No flow of sewage sludge and Acti-zyme into the bio-digester	Pipe blockage Valve fails to open (control valve failure) Pump failure Pipe leakages	Less biogas production No sewage sludge and Acti-zyme in the bio-digester Low biogas yield	Install flow alarms Maintenance (repairing the control valve and pipes) Check valves regularly Install sensors that detect detects any changes and gives feedback
More	Flow	High flow (overflow) of the sewage sludge and Acti-zyme	Valve does not close Pump failure. The pump is continuously pumping sewage sludge and Acti-zyme	Overflow of the sewage sludge and Acti-zyme leading to low productivity Acti-zyme activity reduced due to increased substrate concentration	Install sensors to detect and provide feedback Install level meters and high flow alarms Pumps and valves should be continuously checked and maintained
Less	Flow	Low flow of sewage sludge	Clogging of the sewage sludge	Low yield of biogas Acti-zyme does not have substrate	Install flow meters Alarms

		and Acti-zyme	and Acti-zyme inside the pipes Leakage	to act on	Constant repairs of valves and pipes
More	Pressure	Pressure > 1 atmos	Build-up of gases during the digestion process	Bursting of the bio-digester	Install pressure relief valve to purge the excess gases inside the bio-digester
Less	Pressure	Pressure < 1 atmos		Causes mechanical stress on the bio-digester	Install pressure sensors to detect changes in the pressure
NO	Agitation	No agitation inside the bio-digester	Stirrer motor not functioning	No mixing Possible accumulation of sewage sludge at bottom of bio-digester Acti-zyme cells tend to clump together Rate of digestion is slower Low retention time	Maintenance of the stirrer motor
More	Agitation	More agitation inside the bio-digester	Stirrer motor control fails (high motor speed)	More collision of Acti-zyme and may result in breakage of the cells	Repair of the stirrer motor

4. Conclusion

A bio-digester for sewage sludge digestion using Acti-zyme as bio-catalyst was designed and constructed putting into consideration process safety especially when Acti-zyme is involved. The bio-digester can be up-scaled and down scaled that can be used at both industrial and laboratory scale.

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