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A Simple Method in Evaluating the Performance of H_2S Scrubber at Existing Biogas Plant

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Abstract

Biogas as one of the renewable energy sources contains hydrogen sulfide (H_2S) which causes equipment corrosion and gives negative impacts on the environment. To study some factors that affect the H_2S removal efficiency, evaluation was done on the performance of existing H_2S scrubber. For the case study, it was found that the existing scrubber performance did not reach the target (< 200 ppm-v H_2S) with 1,450 Nm^3 biogas/h and 2,550 ppm-v H_2S inlet (-10 mbarg and 35°C). Scenarios were made by varying the design parameters of the H_2S outlet scrubber (0 - 1,140 ppm-v), H_2S inlet scrubber (2,550 and 3,000 ppm-v), and biogas flow (1,450 and 1,700 Nm^3 biogas/h). Based on the analysis results, it was found that the initial design had already considered an overdesign factor of at least 52 times. Through solubility and residence time analysis, favorable scrubber operation is to run at low liquid spray flow (~ 70 m^3/h). In addition, low flow liquid spray could help activate the bacteria on the bio-packing media surfaces so that they are not eroded by the high erosive spray velocity. This study's results are expected to be a reference for the biogas industry in evaluating the performance of H_2S scrubbers.

Keywords: Hydrogen Sulfide (H_2S), Biogas, Scrubber, Performance Evaluation, Solubility, Residence Time.

INTRODUCTION

Biogas is one of the potential renewable energy sources as an alternative to fossil fuels (Abdeshahian et al., 2016). Biogas can be directly used as fuel for burners to generate steam in boilers (Mittal et al., 2018). Utilization of such biogas for burner fuel can reduce steam production costs (Kapoor et al., 2019). In addition, biogas can also be used as fuel for generators (gas engines). The electricity produced from gas engines can be used to meet electricity needs both for the factory itself and sold to the state electricity company. Biogas is produced through the anaerobic digestion process of organic materials such as agricultural waste, animal waste, and industrial waste. The main components of biogas not only consist of methane (CH_4)

around 55%-v and carbon dioxide (CO_2) around 40%-v, but it also contains a number of impurities such as hydrogen sulfide (H_2S) of approximately 3,000 ppm-v.

Hydrogen sulfide is a highly toxic gas (Guidotti, 2010). At very low concentrations, it can cause irritation to the eyes, nose, and throat (Occupational Safety and Health Administration (OSHA)). The human sense of smell can detect H_2S as low as 0.02 ppm-v. However, this cannot be relied upon as a detection tool because olfactory fatigue occurs at higher concentrations, making it extremely dangerous. High concentrations of H_2S and prolonged exposure reduce the ability to smell, increasing the risk of poisoning. The threshold limit value (TLV) for long-term exposure is set at 10 ppm-v. Symptoms of toxicity appear after several hours of exposure to 100 ppm-v H_2S (Barsan, 2007). The maximum concentration that can be inhaled for 1 hour without serious effects, such as eye and respiratory irritation, is 200–300 ppm-v (EPA ORD NCEA Integrated Risk Information System). Exposure to 500–700 ppm-v for 30 minutes to 1 hour is extremely dangerous, leading to rapid unconsciousness. Fatality occurs in less than 30 minutes at 700–900 ppm-v, while concentrations exceeding 1,000 ppm-v cause death within minutes due to respiratory paralysis. Additionally, H_2S is highly flammable, with an explosive range of 4.3–45% by volume in air (Occupational Safety and Health Administration (OSHA). Due to its density heavier than air, H_2S tends to accumulate near the ground when released into the environment. In addition, the presence of H_2S in biogas plants also causes various problems, including corrosion of equipment, decreased energy efficiency, and negative impacts on health and the environment due to its toxic and unpleasant odor. Therefore, the removal of H_2S is a critical step in biogas purification before further use.

One of the H_2S scrubbing processes for biogas plant scale is the Shell–Paques™ process, commercially known as Thiopaq O&G™. This method relies on biocatalytic conversion, where sulfide is transformed into elemental sulfur under near-ambient conditions (30-40°C and atmospheric pressure), ensuring operational safety. In the process chemistry, the treatment process can be tailored based on the gas stream composition and involves three key stages. The first stage is absorber (or Gas Washing) where a dilute alkaline solution captures H_2S from the sour gas via reaction **Equation (1).**

$$H_2S + NaOH \rightarrow NaHS + H_2O \quad \textbf{(1)}$$

$$NaHS + 0.5O_2 \rightarrow S + NaOH \quad \textbf{(2)}$$

The second stage is bioreactor for sulfide oxidation & liquid regeneration. The absorbed NaHS is biologically oxidized to elemental sulfur (95% selectivity) by specialized microbes *Halo-thiobacillus sp.*, following reaction **Equation (2)**. The regenerated NaOH solution is recycled back to the absorber. Finally, the third stage is sulfur recovery where the biogenic sulfur is separated as a slurry or cake (up to 65% solids). This byproduct can be further processed into sulfuric acid, fertilizers, or fungicides. Other biogas desulfurization technologies are owned by Biogas Clean™, namely the Moving Bed Reactor (MBR) and Bio Trickling Reactor (BTR) types. The selection of these two technologies to remove H_2S from biogas is highly dependent on the biogas flow rate. For capacities below 1,000 Nm^3/h, BTR is generally more cost efficient, while MBR is superior for flows above 1,000 Nm^3/h. In terms of chemical processes and reactor media, BTR relies on the full oxidation reaction of H_2S to sulfuric acid (H_2SO_4) with high oxygen consumption (100%), using a fixed bed. While MBR facilitates partial oxidation of H_2S to solid

sulfur elements (S) with lower oxygen requirements (25%) and by using a moving bed that reduces the tank volume by 25-30% compared to BTR. In terms of operation and maintenance, BTR requires 48-72 hours for initial start-up and 6-9 days/year of routine maintenance, while MBR can be fully operational in 0.5-2 hours with only 1-2 days/year of maintenance. The outlet gas pressure of MBR reaches 150 mbar (without additional compression), in contrast to BTR which is only 10-30 mbar. In terms of impact on biogas composition and the environment, BTR causes 12-21% CH_4 dilution due to the use of air, while MBR is only 5-16%. When using pure oxygen, CH_4 dilution in MBR drops drastically to 1-2%. BTR effluent is highly acidic (pH 1-3), in contrast to MBR which maintains a neutral pH (7), making it more environmentally friendly. In terms of sulfur recovery, the main advantage of MBR is its ability to recover sulfur through sedimentation, cyclones, or centrifugation, while BTR does not allow recovery because sulfur is converted into acid.

In a 149-day pilot test on real farm biogas, a countercurrent bio-trickling filter (BTF) used diluted farm digestate (as inoculum and nutrient) under nitrate respiration (Lenis et al. 2023). The unit treated fluctuating H_2S loads up to 8.5 g S-H_2S·m^{-3}·h^{-1} and achieved 99.2% H_2S removal at peak load. The system-maintained pH 7.5–4.6 without control and supported both anaerobic and anoxic sulfide-oxidizing microbes. The authors conclude that this anoxic BTF with digestate is robust and viable for industrial-scale desulfurization. In a 226-day field trial, the authors fed raw municipal-solid-waste biogas (H_2S up to ~11,000 ppmv) through a pilot BTF inoculated with wastewater sludge. They controlled the process via nitrate dosing to stimulate sulfide-oxidizing denitrifiers. Under varying loads (0.43–61.7 g S-H_2S·m^{-3}·h^{-1}), the filter consistently removed >93.9% of H_2S, with a peak elimination capacity of 35.17 g S-H_2S·m^{-3}·h^{-1} at ~95% efficiency. Sulfate was the main oxidation product (>85% selectivity) and any excess H_2S led to elemental sulfur formation that was later oxidized during low-load periods, avoiding process shutdowns. These results demonstrate that an anoxic BTF can effectively scrub H_2S from high-strength biogas under realistic industrial conditions.

The study by Torres-Herrera et al. (2024) tested a full-scale absorption–bioreactor unit on landfill biogas. By increasing the liquid recirculation rate, H_2S removal rose from 76±8% (6.2 g S-H_2S·m^{-3}·h^{-1}) at low liquid velocity to 97.7±0.5% (8.0 g S-H_2S·m^{-3}·h^{-1}). At an intermediate recirculation (161.4 m·h^{-1}), outlet H_2S dropped to ~3 ppmv (97% removal) for a week. The maximum observed elimination capacity was 50.8±0.6 g S-H_2S·m^{-3}·h^{-1} (96±1% removal). Batch tests and community analysis showed >60% sulfur recovery and identified key sulfur-oxidizing taxa (e.g. *Thioalkalispira* and *Arcobacteraceae*) under different loads. This pilot bioscrubber effectively removed H_2S from real gas with >96% efficiency under optimized conditions. Other study by Arıman & Koyuncu (2021), at an urban wastewater treatment plant with mesophilic digesters, the authors operated a full-scale BTF on high-rate sludge biogas (~18,000–21,000 m^3/day). Inlet H_2S averaged ~3,632 ppmv (range 2,900–4,400 ppmv) and was reduced to ~16 ppmv at the outlet. The system reached a maximum sulfur elimination capacity of 52.7 g H_2S·m^{-3}·h^{-1}. Overall removal efficiency was 97.8–99.9% across all conditions. This real-scale BTF therefore demonstrated very high H_2S removal (down to trace ppm levels) in an industrial wastewater setting.

Based on the above previous researches, the problems raised in this paper include: (1) what is an effective method to remove H_2S in biogas?; (2) what are the advantages and

disadvantages of each method?; and (3) what factors affect the efficiency of H_2S removal? To answer these problem formulations, a case study is taken as the basis for the discussion on the H_2S scrubber operating unit in an existing biogas plant. Details related to the existing H_2S scrubber (sizing, internals, operating conditions, and so on) are explained in the Materials section (subsection 2.1). The performance of this H_2S scrubber will be evaluated. From the evaluation results, several recommendations will be given that can improve the performance of the existing H_2S scrubber. Thus, this paper has several objectives including: (1) evaluating the performance of the H_2S scrubber in an existing biogas plant; (2) studying the factors that affect the efficiency of H_2S removal; (3) analyse the effectiveness and feasibility of each recommendation given from the results of the H_2S scrubber performance analysis based on technical, economic (Rotunno et al., 2017), and environmental aspects (Cavaignac et al., 2021).

The results of this study are expected to be a reference for the biogas industry in evaluating the performance of H_2S scrubbers, thereby improving biogas quality, extending equipment life, and reducing environmental impacts. In addition, this paper can also be a basis for developing more efficient H_2S removal methods in the future.

METHODS

This paper is compiled based on field experiences & literature studies from various scientific sources, including journals, books, and research reports related to H_2S removal technology in biogas. The case studies taken are described through the following explanation below. Biogas from the digester (green arrow in Figure 1) with an installed capacity of 1,500 Nm^3/h containing 60%-v CH_4, 34%-v CO_2, 0.1%-v O_2, and 2,550 ppm-v H_2S and 6%-v unknown gas (estimated as NH_3 and H_2), enters two scrubber units (H_2S removal unit) with an inlet pressure of -2 mbarg and an inlet temperature of 35°C. The scrubber inlet is also injected with atmospheric air (blue arrow) blown by an air blower with a total flow capacity of 16 ~ 60 m^3/h. Inside the scrubber, a total of 75 m^3/h of bacterial liquid is sprayed from the recirculation pool (red arrow) for each scrubber which is divided into each compartment section.

The chemical oxygen demand (COD), nitrogen (N), phosphorus (P), and potassium (K) content of the liquid pumped into the H_2S scrubber are presented in Table 1. The NPK content in the wastewater functions as essential nutrients for bacterial growth and metabolism (Ge et al., 2017; Güneş et al., 2019). For the pH data of this recirculation pool is around > 7. While for the operational system of the scrubber recirculation pool is when the pH is < 6, which means saturated with H_2S, then the circulated liquid is replaced with waste liquid from the pond's mill until the pH is > 7.

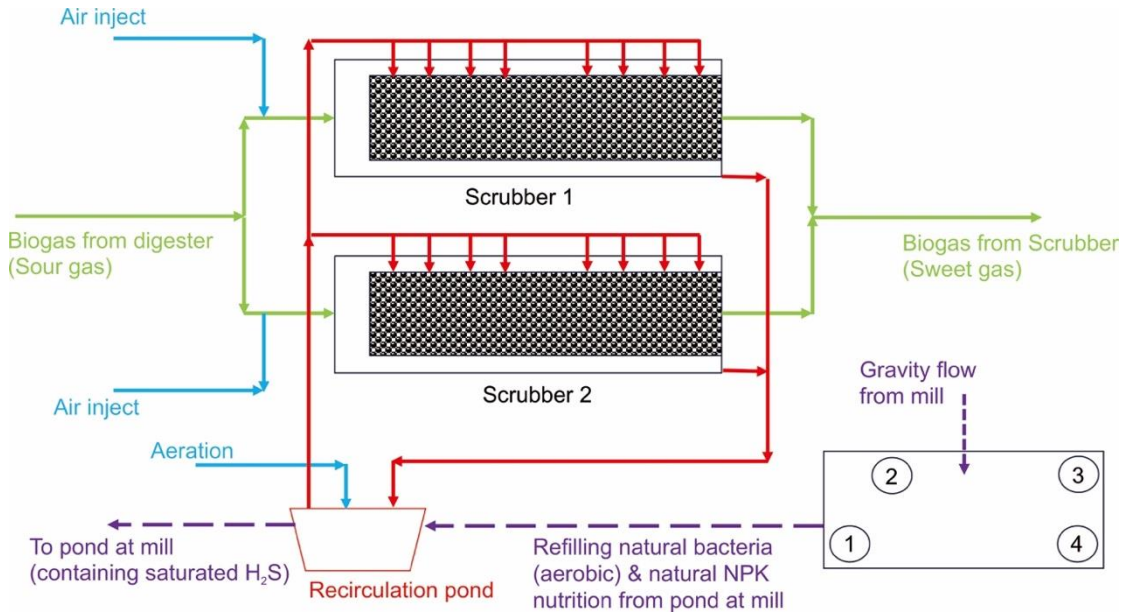

Figure 1. Process flow diagram (PFD) of aerobic biogas desulfurization with liquid waste-water spray from the mill. The numbers in the lower right box are defined in Table 1.

Table 1. Results of laboratory analysis of waste liquid in the mill pond.

Point number from Figure 1	Legends	COD (ppm)	N (ppm)	P (ppm)	K (ppm)
1	Region which is being pumped to recirculation pond	3690	274	402	691
2	Region which is being pumped to Land Application (LA)	4360	533	652	1163
3	Dead zone	4470	561	686	1212
4	Dead zone	4270	428	556	1060

There are 8 compartments inside the scrubber with the dimensions of each compartment being 2.1 m x 1.2 m x 1.75 m (L x W x H). The biogas flow-path in the scrubber is "U" shaped with a partition in the form of HDPE membrane lining that divides the middle of the scrubber. Thus, the scrubber containing the media bio-packing in the container has a total superficial dimension of 8.3 m x 2.35 m x 1.75 m (L x W x H) for one container. In the internal scrubber section, there is an empty space at the bottom of the scrubber of 250 mm which during operation is filled/soaked with drain fluid which is maintained at an elevation of 60 cm from the bottom of the container. This is done so that gas cannot fill the bottom of the scrubber platform & cannot directly bypass moving to the compartment on the other side of the U-path. In addition, the liquid level in the container of 60 cm is also intended so that no liquid is sucked out with the biogas outlet, with the distance of the suction pipe to the bottom of the scrubber being 1 m.

For the bio-packing media used, the material specifications are 50%-PP and 50%-PE. Based on previous dimension data, the total volume of empty space for the media for 2 scrubber units is 68.3 m^3 without considering the porosity (i.e. 90%) of the media. Thus,

through simple calculations, the total area of gas-liquid contact in the media is 9,557 m^2 with a fluid volumetric of 75.85 m^3.

Procedure

The flowchart procedure of the performance evaluation analysis of the existing H_2S scrubber is shown in **Figure 2.** The process begins by setting the target amount of H_2S at the outlet condition. This step is the basis for calculating how much H_2S needs to be removed from the system. After that, the liquid spray flow rate required to absorb H_2S is used with the appropriate unit. Furthermore, the H_2S loading rate is calculated to ensure process efficiency. The results of this calculation are then compared with the solubility data or H_2S loading rate listed in the reference. If the comparison shows that the design does not have an overdesign factor, then it can be said that the design is inadequate and needs to be improved. Here, overdesign factor is defined as the ratio between literature value of H_2S solubility in H_2O with respect to design loading value of H_2S in liquid spray (see **Equation. (10)**). However, if the comparison results meet the criteria (i.e. 20-30 times design loading value), the process continues by checking the residence time. This residence time includes two aspects, namely the liquid spray residence time and the biogas residence time in the scrubber. The final stage involves mass transfer analysis using Henry's law and air injection flow analysis. Air injection is mandatory either to facilitate H_2S oxidation, giving the aerobic bacteria to respire, or to enhance stripping/mass transfer. These analyses aim to ensure that the H_2S removal process is running optimally. Thus, this flowchart illustrates the systematic steps in evaluating and optimizing the H_2S removal process in biogas.

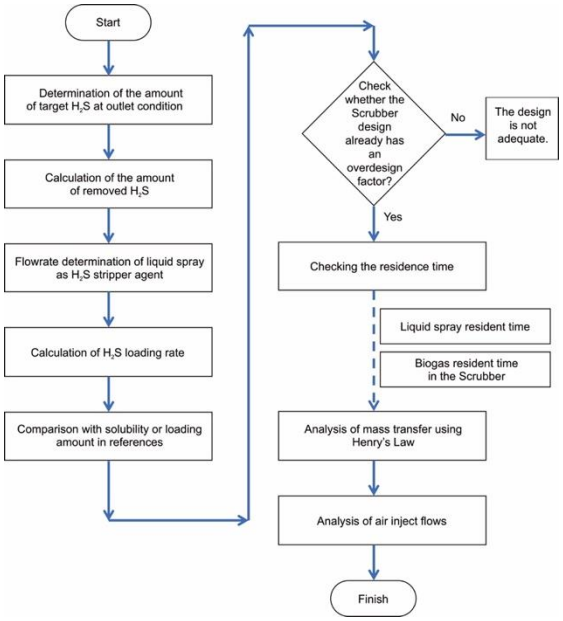

Figure 2. Flowchart of the existing H_2S scrubber performance evaluation analysis procedure.

Calculation

The analysis was conducted qualitatively and using a simple quantitative method to evaluate the performance of the H_2S scrubber through physical, chemical, and biological calculation methods in reducing H_2S levels. Thus, this paper will discuss in depth the performance evaluation method of the H_2S scrubber process unit in a biogas plant along with its implications for the sustainability of the biogas industry. Quantitatively, the following are **Equation (3)–(10)** used in this paper.

$$H_2S\ flowrate\ (Nm^3/h) = \frac{ppmv}{1{,}000{,}000} \times flow\ biogas \quad \textbf{(3)}$$

$$H_2S\ actual\ volume\ rate\ (m^3/h) = H_2S\ flowrate \times \frac{T_{Scrubber}}{273.15\ K} \quad \textbf{(4)}$$

$$H_2S\ mole\ flow\ (mol/h) = H_2S\ actual\ volume\ rate \times \frac{P_{Scrubber}}{R \times T_{Scrubber}} \quad (5)$$

$$H_2S\ mass\ flow\ (kg/h) = H_2S\ mole\ flow \times Mr_{H_2S} \quad (6)$$

$$H_2S\ loading\ rate = \frac{H_2S\ mole\ flow}{Liquid\ spray\ mole\ flow} \quad (7)$$

$$Residence\ time\ (min) = \frac{Contact\ volume\ (m^3)}{Pump\ flowrate\ (\frac{m^3}{min})} \quad (8)$$

$$Contact\ volume\ (m^3) = \frac{Total\ volume\ (m^3)}{Voidage\ ratio} \quad (9)$$

$$Overdesign\ factor = \frac{Literature\ Value\ of\ H_2S\ Solubility\ in\ H_2O}{Design\ Loading\ Value\ of\ H_2S\ in\ Liquid\ Spray} \quad (10)$$

RESULTS AND DISCUSSION

H_2S Removal Performance

Based on the data in the case study in the

subsection 2.1, the performance of the existing scrubber was evaluated & it was found that the H_2S outlet scrubber did not reach the target below < 200 ppm-v. As a representative data, biogas flow data of 1,450 Nm^3/h, H_2S inlet composition of 2,550 ppm-v, scrubber pressure of -10 mbarg (100.325 Pa), and temperature of 35°C, and H_2S outlet scrubber 1,140 ppm-v were used. So that the values are obtained as listed in **Table 2**. The amount of H_2S that has been successfully removed in the scrubber is 3.08 kg/h (or equivalent to 55.3% removal). For the flow of biological water spray is assumed to be lower than the design to accommodate pressure drop loss, and the total flow value is taken as 140 m^3/h. With a temperature of 35°C, the density of water is 993 kg/m^3 (IAPWS, 2018), so that the total spray mass flow rate is 139,020 kg/h or equivalent to 7.72×10^6 mol spray per hour. So that the final calculation will get the H_2S loading rate (top section). As a reference comparison, the solubility of H_2S in pure liquid H_2O is 1.50×10^{-3} mol H_2S/mol H_2O at standard conditions. While H_2S removal with amine process generally has loading rate values (bottom section) presented in **Table 3**.

Based on the calculations & reference data above, the H_2S loading data on the existing scrubber with wastewater containing natural bacteria from the mill waste pond is much lower 128 times compared to the solubility of H_2S in pure H_2O (1.17×10^{-5} vs. 1.50×10^{-3} mol H_2S / mol H_2O). So, it is necessary to further examine the causes of the low solubility of H_2S in the existing wastewater. Therefore, the authors want to study the value of the overdesign factor in the existing design. Then a scenario was carried out by varying the parameters of the H_2S outlet scrubber, H_2S inlet scrubber, and biogas flow, the calculation results of which are presented in **Figure 3.**

Table 2. Conversion values of the amount of H_2S successfully removed.

Parameters	Values	Units
H_2S inlet flowrate	3.70	Nm^3/h (at 273.15 K)
H_2S inlet actual volume rate	4.17	m^3/h (at 308.15 K)
H_2S inlet mole flow	163.35	mol/h
H_2S inlet mass flow	5.57	kg/h
H_2S outlet flowrate	2.04	Nm^3/h (at 273.15 K)
H_2S inlet mass flow rate	2.49	kg/h
Removed H_2S	3.08	kg/h

Table 3. H_2S loading rate values in liquid spray. (VL = vapor-liquid, MEA = monoethanolamine, DEA = diethanolamine, MDEA = methyl-diethanolamine)

Parameters	Values	Units
H_2S loading rate (actual)	1.17×10^{-5}	mol H_2S / mol biologic spray
	1.65×10^{-5}	m^3 H_2S / L spray
	322.25	mg H_2S / m^2 VL contact area on media / h
	40,604	mg H_2S / m^3 VL contact volume on media / h
H_2S loading rate (reference)[a]	0.33 – 0.40	mol acid gas / mol MEA
	0.023	m^3 acid gas / L MEA
	0.35 – 0.65	mol acid gas / mol DEA
	0.029	m^3 acid gas / L DEA
	0.20 – 0.55	mol acid gas / mol MDEA
	0.022	m^3 acid gas / L MDEA

[a](Gas Processors Suppliers Association (GPSA)

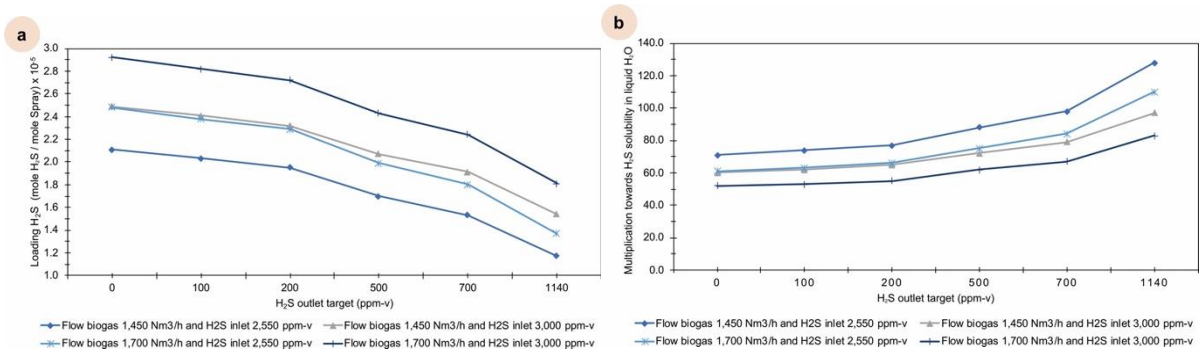

Figure. 3. Effect of target H_2S outlet in scrubber design on (a) H_2S loading in waste liquid and on (b) multiplication of H_2S solubility data in pure liquid H_2O (1.50 x 10^{-3} mol H_2S / mol H_2O).

From **Figure 3**, it can be found that the initial design has considered an overdesign factor of at least 52 times and has an over-spec of biogas flow of 1,700 Nm^3/h and H_2S inlet of 3,000 ppm-v. However, the calculation uses the assumption that the residence time of the biogas fluid & waste spray is infinite. Thus, the calculation of the actual residence time on the media surface is needed. The rigorous calculation method is to perform particle tracing simulation (Elghobashi, 2019).

Liquid-Gas Residence Time Analysis

To simplify the calculation without ignoring the overdesign factor, the calculation of the liquid spray residence time in the scrubber is carried out as follows with the height of the occupied hold-up of the liquid in the scrubber being 60 cm. With a container width of 2.35 m and a container length of 9.3 m, the volume of drain liquid in 1 scrubber held (hold-up) is 13.4 m^3 and the volume of drain liquid in 2 scrubbers held (hold-up) is 26.8 m^3. Then the residence time is 11 minutes with a spray pump flow of 140 m^3/h. The trend based on this calculation is, the lower the spray pump flow, the longer the residence time of the liquid in the scrubber. For example, the spray pump is only run 1 unit for 2 scrubber units, then the residence time will be 22-23 minutes.

However, the hold-up residence time only considers the liquid that pools at the bottom of the scrubber. To consider the duration of contact time between biogas and spray liquid representing active bacteria on the surface of the bio-packing media, the calculation was carried out again. With a total media volume considering porosity of 75.85 m^3, the residence time is 33 minutes. As an additional consideration, the liquid-gas contact velocity is also calculated with a total media surface area of 9,558 m^2 so that the contact velocity is obtained at 4.1 μm / s. The trend based on this calculation is also the same, indicating that favorable operations are run at the lowest spray pump flow, the lower the spray pump flow (Wu et al., 2021), the longer the gas-liquid contact velocity.

Mass Transfer and Henry's Law

Additional calculations are required to correlate residence time (contact efficiency) with the liquid-phase saturation capacity of H_2S, particularly regarding mass transfer from gas to liquid phases. This correlation enables system balancing—when biogas flow increases, the spray pump flow must be proportionally increased to maintain H_2S loading rates (Jenícek et al., 2017). As illustrated in Figure 4, H_2S mass transfer can be enhanced through biochemical reactions facilitated by active bacteria, including:

1. endogenous Thiobacillus sp. in biogas which naturally formed during anaerobic

digestion and transported to the scrubber (Carabeo-Pérez et al., 2019);

2. activated Thiobacillus sp. in scrubber liquid which cultivated in aerated recirculation ponds;
3. biofilm-immobilized Thiobacillus sp. which colonized on bio-packing media surfaces.

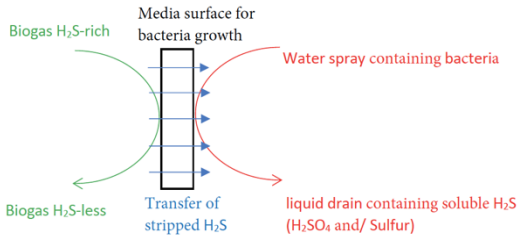

Figure 4. Illustration of H_2S mass transfer from biogas to liquid spray.

Thiobacillus species bacteria function as bio-enzyme catalysts that selectively accelerate the conversion of H_2S into either elemental sulfur (S) or aqueous sulfuric acid (H_2SO_4), following the biochemical pathways detailed in reactions **Equation (11) – (13)** (Ortiz et al., 2020; Huynh Nhut et al., 2020; Qiu & Deshusses, 2017).

$$2H_2S + O_2 \xrightarrow{Thiobasilus\ sp.} 2S + 2H_2O \quad \textbf{(11)}$$

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 \quad \textbf{(12)}$$

$$Total\ Reaction: \quad 2H_2S + 4O_2 \rightarrow 2H_2SO_4 \quad \textbf{(13)}$$

From the reactions, two conclusions are obtained, namely: (1) if the amount of oxygen supplied is small, then what is formed is elemental sulfur which can settle / cover the surface of the media, and (2) if the amount of oxygen supplied is excessive, then what is formed is aqueous H_2SO_4 which is dissolved in the recirculation fluid.

Evaluation of the amount of air/oxygen supplied can be calculated based on existing data as follows, the mole ratio between O_2 and H_2S is 1 mol: 2 mol, so for H_2S 163.35 mol/h, 81.67 mol O_2/h is needed, or equivalent to 1.31 kg O_2/h. The volumetric flow of O_2 under these conditions is 0.9145 m^3 O_2/h. So, the atmospheric air that needs to be injected is 4.3650 m^3 air/h. For the case of moles O_2 : moles H_2S = 2 mol : 1 mol, so for the same H_2S (163.35 mol/h), 326.69 mol O_2/h is needed, or equivalent to 5.23 kg O_2/h. The volumetric flow of O_2 under these conditions is 3.6578 m^3 O_2/h. So, the minimum atmospheric air that needs to be injected is 17.46 m^3 of air/h.

Effect of Liquid Spray Pump Flow

From the previous calculation related to the residence time of liquid spray on the surface of the bio-packing media (33 minutes) must be matched with the residence time of biogas in the scrubber which is calculated as the residence time required for H_2S raw biogas in the scrubber to disappear completely, which is more than 18 hours of H_2S gas must be in the scrubber (ideally all empty spaces are passed through by biogas). While the short-cut calculation of the residence time of biogas in the superficial scrubber, namely without media (Choudhury et al., 2019), is obtained for 4 minutes. While the residence time of biogas through the media is obtained 4.32 minutes.

As a summary of this calculation, biogas is only 4 minutes in the scrubber while liquid spray has covered longer, namely 33 minutes in the scrubber. The calculation is done again by considering the saturation value of H_2S in wastewater, which is 1.50 x 10^{-3} mol H_2S / mol H_2O. So, for 4 minutes of biogas in the scrubber with a total flow of H_2S load to be removed of 198.8 mol H_2S / h, a liquid spray flow of 2.40 m^3 / h is needed. If considering the 50% overdesign factor, the wastewater spray discharge is 4.80 m^3 / h.

The conclusion that can be drawn based on the solubility data above (it is also recommended to refer to the calculation using

the equation involving Henry's Law constant), is that with the current existing liquid spray flow of 140 m^3/h it is very safe with an overdesign of 98.3% compared to the pure solubility value. However, this does not compensate for the contact residence time of the liquid with the gas in the scrubber for 33 minutes. So, if only 1 pump is run (i.e. 70 m^3/h), then the affinity of H_2S to H_2O increases 96.5% with respect to the solubility with pure H_2O, and the residence time becomes 65 minutes. If referring to the Henry's Law equation, with the constant H of 1 x 10^{-3} mol H_2S / m^3 H_2O / Pa (Sander, 2023), then it can be calculated through **Equation (14).**

$$L = k \times GH(y_0 - y) \qquad (14)$$

where L is the requirement of H_2O, G is the mole rate of gas, H is Henry's constant for H_2S and H_2O, k is the overdesign factor, y_0 is the input H_2S concentration, y is the output H_2S concentration. So, assuming the H_2S output is 10 ppm-v; L = 1.25 x 67,647 mol biogas/h (equivalent to 1,600 Nm^3 biogas/h) x 0.01015 m^3 H_2O/mol H_2S x (0.003 – 1x10^{-5}) = 2.57 m^3 H_2O/h.

So based on the discussion of Henry's Law, solubility data, and residence time, favorable scrubber operation is to run a low liquid spray flow. In addition, low liquid spray flow also functions to help activate the bacteria on the surface of the bio-packing media so that they are not eroded by erosive spray velocity (Kabeyi & Olanrewaju, 2022) that are too high. While the high flow spray helps rinse elemental sulfur solids on the surface of bacteria / on the surface of the media so that it is suitable for use in maintenance operations to clean H_2S solids in the scrubber.

Effect of Air Injection Flow

At a small amount of injected air, at least 17.5 m^3 of air/h (calculated based on the reaction stoichiometry), & previous operations have been carried out at an air flow of 16 m^3/h, then what is formed is elemental sulfur that can settle / cover the surface of the Media. The advantage of this operating flow mode is that the liquid will not be quickly concentrated by H_2SO_4 so that the waste solution that is sprayed in contact with biogas will have a stronger binding energy amount to H_2S. However, the weakness of this low air flow mode is that the surface area of bacteria / media will be covered by elemental sulfur more quickly than in the excess air flow mode, which results in maintenance having a more frequent frequency & time is needed for bacterial re-activation.

While in the amount of air injected excessively, in the previous operation that has also been done at a flow of 60 m^3/h, then what is formed is aqueous H_2SO_4 dissolved in the recirculation fluid. With the advantages & disadvantages of this mode is the vice versa with respect to the low air flow operation mode. The impact is, the fluid will acidify more quickly (rapid pH decrease) so that a recirculation fluid buffer is needed which can be taken from the pond waste in the mill (Rattanaya et al., 2021), including NPK nutrients for Thiobacillus species bacteria. There is a note that a little discharge of recirculation pond fluid is needed to maintain the liquid-level of the recirculation pond (Zhu et al., 2020). The quantity & type that is discharged must not be bacteria, but aqueous water and/or dissolved H_2SO_4 (Oliva et al., 2020). To do so, the suction of the waste pump can be suggested to hang or float at the elevation level in the middle (Wilson et al., 2024) where there is no bacterial sediment (which such bacteria is mostly in fact is at the bottom & is floating in the recirculation pond).

CONCLUSION

Based on the discussion of Henry's Law,

solubility data, and residence time, it is concluded that operating the H_2S scrubber with a low liquid spray flow is more favorable, as it not only optimizes gas-liquid contact but also protects surface bacteria on the bio-packing media from erosion caused by excessive spray velocity. While high spray flow is beneficial during maintenance for rinsing elemental sulfur from the media, its continuous use is less efficient. Similarly, low air injection flow helps prevent rapid acidification of the liquid phase, maintaining a stronger H_2S binding capacity, but increases the risk of sulfur buildup that can inhibit bacterial activity, requiring more frequent maintenance and reactivation. Conversely, high air flow reduces sulfur buildup but accelerates acidification, necessitating the use of a recirculation buffer. These findings offer valuable insights for the biogas industry to optimize scrubber performance, improve biogas quality, extend equipment lifespan, reduce environmental impact, and serve as a foundation for future advancements in H_2S removal technologies.

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