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Design and Manufacture of a Biogas Measuring Device Produced by the Anaerobic Digestion of Organic Waste

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Abstract. The production of biogas through anaerobic digestion of organic waste has been recognized as a promising source of renewable energy. Accurate measurement of biogas production is crucial for studying the effect of different parameters affecting the production of biogas. In depth theoretical study was carried out to design and manufacture a biogas measuring device that can measure a very small volume of gas (2-20 mL) at very low pressures (close to atmospheric pressure) with high accuracy (18.95 ± 0.16 mL) that met the laboratory work requirements. The device utilizes the principle of liquid displacement and buoyancy to measure the volume of biogas produced during anaerobic digestion. The device was calibrated using a known volume of gas and then tested it. The results showed that the device was able to accurately measure the biogas production rate. The device is easy to use, affordable and can be scaled up for use in larger anaerobic digestion systems. The successful design and manufacture of this biogas measuring device will contribute to the efficient and effective operation of anaerobic digestion systems and the utilization of renewable biogas as a source of energy.

Keywords: volumetric method, anaerobic digestor, liquid displacement, gas measurement standardization, wet gas

Introduction

Biogas production from organic waste has gained increasing attention as a promising source of renewable energy. Organic waste such as agricultural residues, food waste and sewage sludge can be transformed into biogas through anaerobic digestion (a process that involves the breakdown of organic matter by micro-organisms in the absence of oxygen) (Fan *et al*., 2018).

There are several operating factors affecting the production of biogas in the AD process. These mainly include temperature (Chen, 2014) and hydraulic retention time (HRT) (Singh *et al*., 2018; Moestedt *et al*., 2013), organic loading rate (OLR) (Lee, 2009; Kim *et al*., 2003) and pH. Other factors affecting the gas production also include tank volume, feedstock type, feeding pattern and carbon to nitrogen (C/N) ratio (Bhatt and Tao, 2020). The main indicator of the effect of this factor on the performance of an anaerobic digester is the amount of gas produced. Thus, measuring the volume of biogas accurately is crucial to monitor the operation of the digester and optimize its efficiency.

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Measuring a tiny volume of gas at low pressures (close to atmospheric pressure) with high accuracy is not easy and remains to be a challenge. Currently available industrial gas flow measuring devices do not enable us to measure low gas flows with the required accuracy. There are various methods of measuring the volume of gas (Wijekoon *et al*., 2011), but there are two traditional approaches for measuring the volume of gas produced during a unit of time:

Measurement under constant pressure. The principle of this method is that if the pressure of a gas is constant over time, then its volume will be proportional to the mass of the gas produced from the digester. Methods based on this principle are called volumetric methods because the measuring device calculates the volume of gas produced by measuring the displacement of a piston or the displacement of a volume of water using any mechanical calculation method (Stromberg *et al*., 2014).

Measurement under constant volume. The principle of this method is that if the volume of measurement remains constant, the pressure will be proportional to the mass of the gas produced (Rosato, 2018). The methods that depend on this principle are called para-metric methods, as the measuring device (mechanical

manometer, mercury column, etc.) senses the pressure of the gas produced by the anaerobic digester (Rosato, 2018; Guwy, 2004). Then, the volume of gas is calculated corresponding to the pressure increase.

There is another mechanism based on the gas chromatography method, similar to the parametric method where instead of measuring the increase in pressure, the devices measure the changes in gas composition (Wedler, 2022; Walker *et al*., 2009). This method has good measurement accuracy, but the response of the devices is low, and they cannot sense changes less than 75 Ncm^3. In addition, the gas chromatography technique requires expensive devices, a highly experienced operator, and continuous calibration of the devices, which is not suitable.

Through research in our lab, we designed a device that measures the volume of produced gas according to the volumetric method based on the principle of liquid displacement and buoyancy. This device is simple, effective, and utilizes a low-cost mechanism to operate. This device works according to an automatic system based on volumetric gas measurements. It is an integral part of a laboratory simulation system to measure the effect of several factors on the rate and efficiency of gas production (Rosato, 2018).

Material and Methods

Working principle of the device. The bucket in the biogas measuring device works based on the principle of liquid displacement and buoyancy. As the gas enters the device through the gas inlet, it flows through a tube and enters the bucket, which is submerged in a liquid (usually water) contained within a cell. The gas collects in the bucket, displacing an equivalent volume of liquid. As the volume of gas in the bucket increases, the buoyant force acting on the bucket increases. When the buoyant force becomes greater than the force of gravity acting on the bucket, the bucket rises to the top of the cell, and the gas is released from the bucket into the upper space of the device and then out through the gas outlet. After the gas is released, the buoyant force acting on the bucket decreases, and the bucket sinks back into the liquid. The cycle then repeats with the bucket collecting gas until it reaches the point where the buoyant force is greater than the force of gravity again, and the gas is released. The bucket's movement is monitored and recorded by a counting device that generates a digital pulse for each cycle of gas collection and release. The number of pulses corresponds to the volume of gas collected, which can be calculated based on the known volume of the bucket and the number of cycles completed.

Bucket design. ***Work mechanism of the bucket.*** The bucket fixed by the hinge is subjected to the following two forces:

The first force. It is the buoyant force (Ahmed *et al*., 2001) and is equal to the weight of the liquid displaced by the body of the bucket and the gas collected within it before it floats. Its value increases with the increase in the volume of the collected gas. Its value is given by the following equation:

$$F_b = (V_t + V_s + V_g).\ \gamma_w$$

where:

γ_w = The specific weight of water within the device that submerges the bucket; V_g = The volume of gas accumulated within the bucket; V_t = The volume of the attachments (magnet), which is placed within the bucket and helps the sensor in counting the float times of the bucket; Vs = The volume of the solid (polymeric) substance that makes up the bucket; Fb = The buoyant force acting on the bucket and pushes the bucket up and affects the buoyancy center B (Ahmed *et al*., 2001) {the center of the geometry formed by volumes $(Vs + V_t + V_g)$} as shown in Fig. 1.

Given that the bucket is fixed at one end by joint A, this means that the buoyant force works to rotate the bucket around the A-axis in a clockwise direction, and the moment of this force is as follows:

$$M_b = F_b.\ r_b$$

r_b = The buoyant force arm represents the vertical distance between the axis of rotation passing through A and the vertical buoyancy force passing through the point of impact B.

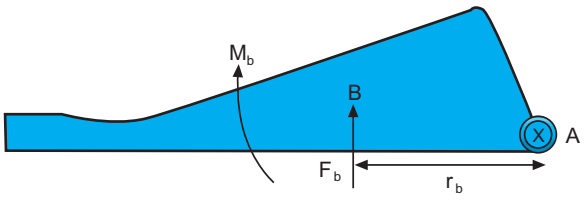

Fig. 1. The buoyant moment of the buoyant force as a result of the gas accumulated within the buycket and affecting the buoyancy center B.

The second force. It represents the weight of the bucket with the gas accumulated in it, and its value is given as:

$$W = W_s + W_g + W_t$$

where:

W_s = weight of the solid (the polymeric material that makes up the bucket); W_g = weight of the gas collected within the bucket is considered negligible due to its smallness; W_t = attachment weights (magnets) which are placed within the bucket to aid in the measurement. This force affects the bucket with a moment that rotates the bucket counterclockwise, as shown in Fig. 2.

The moment of this force is given by:

$$M_w = W.\ r_w$$

W = The weight of the entire bucket; r_w = The arm represents the vertical distance between the axis of rotation passing through A and the vertical weight force passing through the center of gravity G (the center of gravity of the bucket due to the distribution of weights within it).

The buoyant force rotates the bucket upward (clockwise) shown in Fig. 3 and its value increases with the increase in the displaced volume of the liquid due to the continuous accumulation of gas inside it. When the buoyant force moment reaches a value that exceeds the moment of the force caused by weight of the bucket, which acts in the opposite direction, then the bucket floats on the side of the free end. The gas collected below it is released the space upwards above the surface of the water.

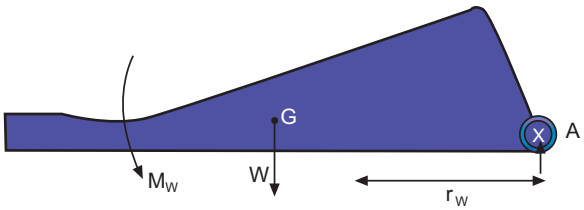

Fig. 2. The moment due to the weight of the bucket acting on the center of gravity G.

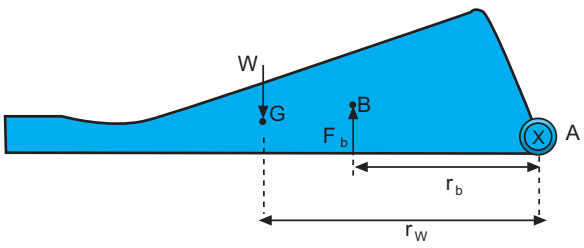

Fig. 3. Shows the forces affecting the bucket and their centers of influence.

When the gas is released, the buoyancy force becomes less than the weight of the bucket and therefore the bucket goes back to diving and starts a new cycle of gas collection. Thus, in each cycle a specific volume of gas is released, which is corrected to standard conditions.

When the equilibrium moment that precedes the buoyancy of the bucket is achieved, we have:

$$M_b = M_w$$
$$F_b.\ r_b = W.\ r_w$$
$$(V_s + V_g + V_t).\ rb.\ \gamma_w = (W_s + W_g + W_t)\ .r_w$$

The previous equation contains the essential variables that help in designing the bucket, thus we have:

$W_g = 0$ as the weight of the gas is negligible; $\gamma_w = 9.81$ grf/cm^3 since water is the liquid that fills the device; W_t = constant = 5.1 gr and V_t = constant = 1.2 cm^3.

Since there is a constant size and weight of the magnet, this helps to count the times of floating and emptying of the cell.

V_g = The maximum volume of gas accumulated within the bucket before it begins to float.

Determination of the maximum volume of gas within the bucket (Vg). The choice of this size relates to as follows:

- Measurement accuracy required (in our case, 15-25 mL is enough)
- The expected gas production (measurement) rate and considering that the bucket can perform two cycles per minute and therefore the bucket's working range (the permissible flow limits): minimum = (Vg) mL/day; maximum = (24×60×2×Vg) L/day

Increasing the rate of gas production above the maximum permissible limit puts the bucket in a continuous state of floating and does not allow the measurement of gas and, thus, the failure of the measurement process, given that the required accuracy = 20 mL and therefore:

Minimum = (Vg=20) mL/day
The maximum: (24×60×2×20 = 57.6) L/day

Considering that the maximum volume of gas produced from any organic matter by anaerobic digestion is approximately equal to: 40 mL/g (VFA)/day (Hao *et al*., 2016; Liu *et al*., 2012; Wijekoon *et al*., 2011) which means 40 mL/g of volatile organic material per day; this means that the device can measure the gas produced by:

$$\frac{57600}{40} \text{ 1440 g of organic matter (FVA) daily}$$

The percentage of volatile organic material within the organic solution subjected to anaerobic digestion represents 10% of it. (Kothari *et al*., 2014; Saker *et al*., 2014). This is an ideal ratio for the anaerobic digestion process. The maximum weight of the solution is:

$$\frac{1440}{0.1} \text{ 14.4 Kg}$$

The volume of the solution represents 60% (Sarker *et al*., 2019; De Gioannis *et al*., 2008) of the total volume of the digester, and therefore the total volume of the digester is approximately (36L), which represents the largest volume of the digester with which the proposed gas measuring device can be used with accuracy (20mL) and when using a digester with a larger capacity, a more significant gas flow will result in an error in the measurement process.

Final bucket design. After selecting the appropriate Vg, which represents the appropriate measurement, the equation 1 becomes as follows:

$$20 = \frac{(W_s + 0 + 5.1).\, r_w}{r_b.\, 9.81} - (V_s + 1.2)$$

$$20 = \frac{(W_s + 0 + 5.1).\, r_w}{r_b.\, 9.81} - (V_s + 1.2)$$

The optimal design must be chosen that achieves Eq. 2, while noting that the geometry of the bucket and the type of material affect the design.

From the previous equation, we find that the basic variables are:

- The geometry of the bucket body that determines the center of the buoyant force acting on it and thus the arm of the buoyant force (r_b) about the axis of the joint A
- The masses are distributed over the entire body of the bucket, which determines the center of gravity force of the bucket and, therefore, the arm of gravity force r_w around the A-axis
- The type of bucket material, which gives the weight of the bucket W_s, in addition to the volume of liquid displaced by it V_s

The bucket was designed by one of the design programs to achieve the previous equation. The design is as shown in Fig. 4.

After completing the design, the values of the basic variables were as follows:

$V_s = 16.8\ cm^3$; $W_b = 22.7$ gr; $r_b = 4.6$ cm; $r_w = 6.18$ cm

When substituting in equation 1, the theoretical size of the bucket (after its design) is:

$$V_g = \frac{(22.7 + 0 + 5.1) \times 6.18}{(4.6 \times 1)-} (16.8+1.2) - 19.34 \text{ mL}$$

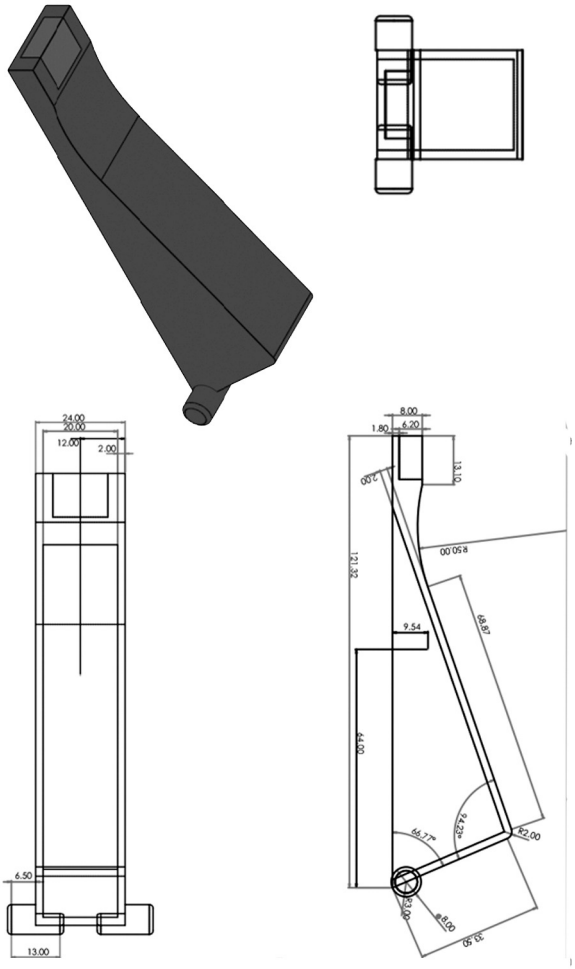

Fig. 4. Design a bucket that achieve the equation (2).

It is the theoretical volume that the gas will occupy before the bucket floats and the gas inside it is released.

Using a 3D printer (Fig. 5 and 6), the bucket and its support were printed that secures it within the cell and its rotation around its axis of rotation. Then the bucket was practically tested to show that the chosen design achieves the size of V_g = 19.34 mL.

Correct the measured gas volume to standard conditions. The device is equipped with electronic sensors for pressure and temperature and an electronic counter for the movement of the bucket. These sensors are connected to a program that automatically corrects the measured volume under working conditions to the standard conditions of pressure and temperature, simultaneously, at each volume release of gas, thus obtaining the volume of gas produced under the standard conditions.

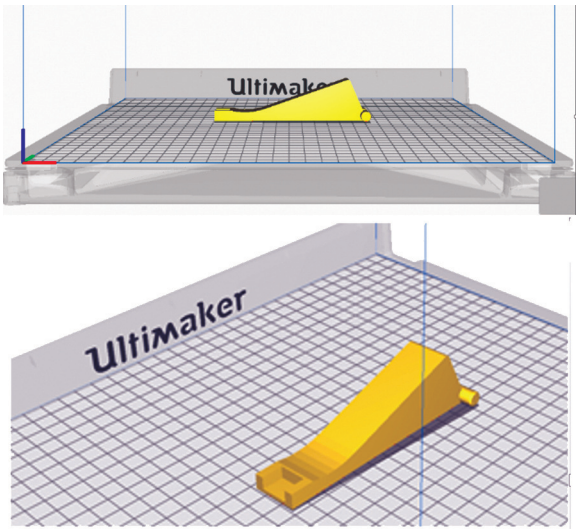

Fig. 5. Putting the design of the bucket on the program (UltiMaker), which is a software for the 3D printer, in preparation for its printing.

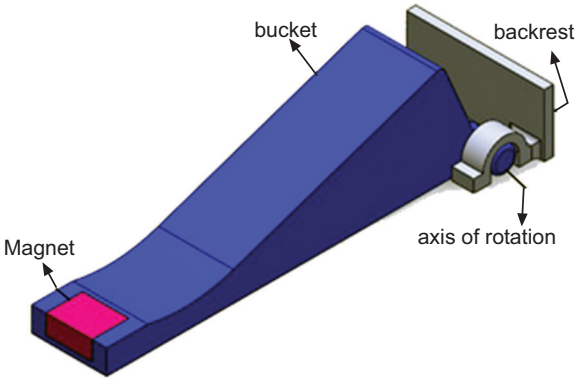

Fig. 6. The bucket with its backrest after being printed using a 3D printer.

The pressure and temperature are measured at each flotation process of the bucket and the release of gas within it. The volume is corrected back to the standard conditions of pressure and temperature (0% humidity, T = 0; P = 1 atm).

There are different standard terms of reference but in general IUPAC (The standards of the International Union of Pure and Applied Chemistry) is approved for use (McNaught and Wilkinson, 2019) which supposes: Standard pressure (P=101,325 Kpa) and temperature (T=0) which meets 0% humidity as shown in Fig. 7.

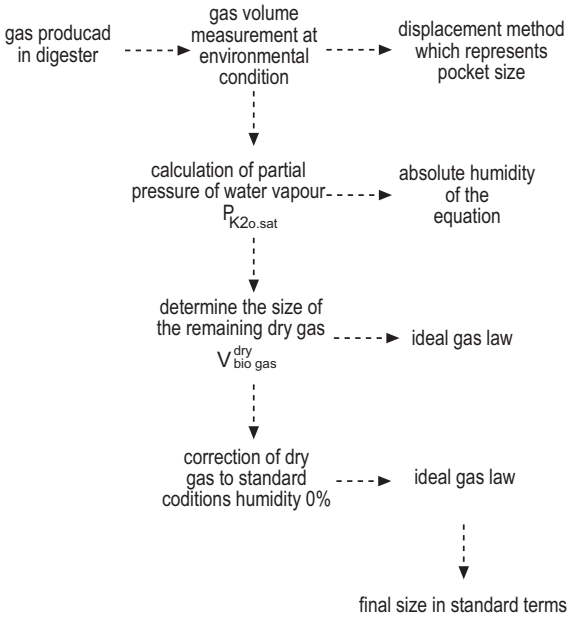

Fig. 7. Diagram illustrating the mechanism for calculating the volume of a gas under standard conditions.

There are two cases (Neubert *et al*., 2021) for calculating gas in standard conditions, which are illustrated by the following Fig. 8.

Results and Discussion

The results in both methods (Neubert *et al*., 2021) are similar and differ slightly, but in the second method, a

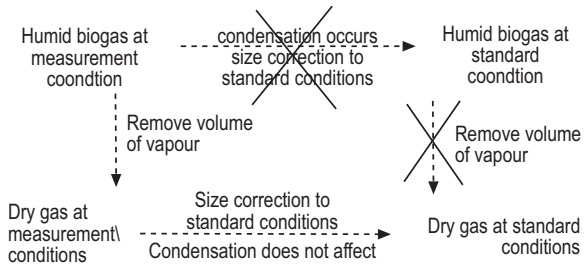

Fig. 8. The best method for calculating the volume of dry gas under standard conditions, starting with wet gas (Neubert *et al*., 2021).

slight error occurs due to the condensation of humidity and consequently an error occurs in calculating the volume.

It is preferable to subtract the volume occupied by water vapor initially before converting the volume to the standard conditions under which humidity condensation and volume reduction occur.

First case. The volume of gas vapour is subtracted from the volume of the gas and then the volume of dry gas remaining under standard conditions is calculated at 0% humidity as follows:

- Calculate the water vapor concentration in biogas using the absolute humidity equation:

$$AH = \frac{m_{H_2O}}{V_{biogas}} = \frac{P_{H_2O},sat}{T_{biogas}.R_{H_2O}}$$

where:

AH = absolute humidity (Kg\m^3); T_{biogas} = Wet gas temperature (Kelvin); R_{H_2O} = Gas constant of water vapour (461.52 J/Kg/K); P_{H_2O},sat = The partial pressure of water vapour in biogas saturated with water vapour. This is calculated from (Antoine) equation (Bierwerth, 2019; Roizard, 2014).

The values of the parameters A, B and C are tabulated (Neubert *et al*., 2021) according to the pressure and temperature conditions of the gas Table 1.

Table 1. The values of parameters (A, B, C) tabulated according to the conditions of pressure and temperature of the gas

A	B	C	T_{min} °C	T_{max} °C
8.07131	1730.63	233.426	1	99
8.14019	1810.94	244.485	100	374

It can also be calculated based on an equation (Magnus):

$$P_{H_2O},sat = 0.611213\ (Kpa).e^{\frac{17.62\times T_{biogas}\ °C}{243.12\ °C + T_{biogas}}}$$

(Neubert *et al*., 2021).

Calculating P_{H_2O},sat in both equations gives very slightly different results and both equations can be used.

- Calculating V^{dry}_{biogas} by calculating V_{H_2O} using the ideal gas law:

$$P.\ V = n.R.T \Rightarrow\ V = \frac{n.R.T}{P}$$

Hence the volume of water vapor can be given as:

where:

m_{H_2O} = mass of water vapour (g); R = Gas constant of water vapor (J/Kg/K); T_{biogas} = Wet gas temperature (Kelvin); M_{H_2O} = Molecular weight of water (18 g/mol); P_{biogas} = biogas pressure (pa)

And therefore:

$$V^{dry}_{biogas} = V_{biogas} - V_{H_2O}\ (m^3)$$

- Convert V^{dry}_{biogas} (gas volume in working conditions) to $V^{STP,\ dry}_{biogas}$ (volume of gas in standard conditions).

And therefore:

$$V^{STP,\ dry}_{biogas} = \frac{P_{biogas}\ \ V^{dry}_{biogas}\ \ T^{STP,\ dry}_{biogas}}{T^{dry}_{biogas}\ \ P^{STP,\ dry}_{biogas}}$$

where:

P_h = Represents the hydrostatic pressure of the liquid (water) within the device, below the bucket as shown in Fig. 9.

$P_h = \rho.g.h$; ρ = water density; g = Earth's gravitational acceleration; min = the water level within the device, which achieves buoyancy of the bucket and thus the full release of gas.

We work to ensure the level of water within the liquid in the range (max-min), where an increase in the level of (max) leads to a measurement error and therefore, we are keen on an average value of h between (–max-min).

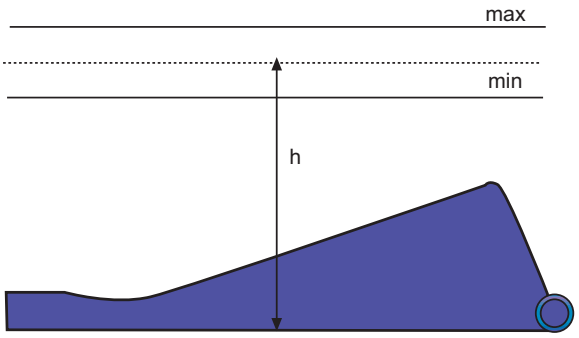

Fig. 9. Showing the height of the liquid immersing the bucket within the cell.

The second case. The volume of wet gas is calculated directly in standard conditions by a complex equation (Neubert *et al*., 2021) that includes the previous two phases in the first case:

$$V_{biogas}^{STP} = V_{biogas}. \frac{(P_{biogas} - 10^{\left(7.19621 \frac{1730.63}{233.426\ °C + T_{biogas}} + \Delta P_{GM}\right)}).T^{STP}}{P^{STP}.\ T_{biogas}}$$

Δ_{PGM} = Pressure loss of the measurement device (can be considered negligible).

The first case was adopted for calculating the volume of the gas as it is the most accurate.

After calculating the gas volume, the data is stored over time in a database and displayed on the interface of a specially designed program to display and analyze the results.

Figure 10 represents the biogas measuring device that was designed and manufactured based on the theoretical study mentioned earlier.

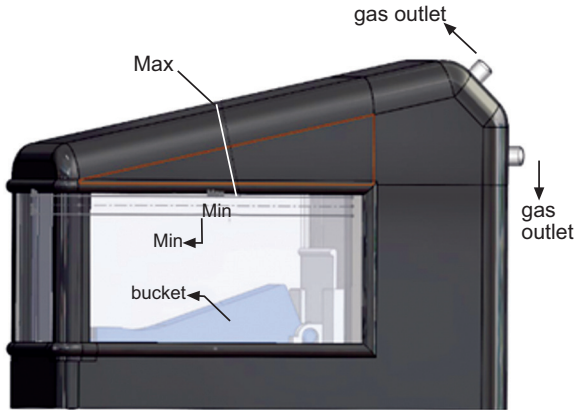

Fig. 10. Gas volume measuring device.

The biogas measuring device is composed of the following components: Gas inlet; Bucket (flow cell); Gas outlet; Required water level indicator; Maximum water level indicator; Minimum water level indicator; Glass for visual verification of bucket movement; Power socket; Digital data socket; Calibration tool to ensure correct horizontal installation and therefore, measurement accuracy.

A counting device generates a digital pulse that represents the specific volume of gas collected below the bucket in units of 0.1 mL. Thus, calculating the number of times the bucket is released is equivalent to calculating the gas flow. The measurement accuracy depends on the specific volume of the bucket (2, 10 or 20 mL) according to the required accuracy. The data is recorded in an integrated data system that displays and analyzes the gas flow data.

The device corrects the volume of gas released from the bucket to standard pressure and temperature conditions (Walker *et al*., 2009) using real-time correction of temperature and pressure in the volume calculations. The correction ensures accurate estimation of the gas volume relative to standard pressure and temperature conditions, reducing errors and saving time and costs associated with retesting and recalibration.

At specific and stable conditions of pressure and temperature (conditions of the room in which the measurement was taken), the device was tested using room air as measuring gas and using a small syringe with a precision of 0.1 mL where the air was injected into the bucket and the results were recorded (calculating the volume of air injected at each operation). The bucket floats and the air injected into it is released. Ten tests were conducted and the results are given in the following Table 2.

Table 2. Experimental results of the device test

10	9	8	7	6	5	4	3	2	1	Test(n)
18.8	19.2	18.9	18.9	18.8	18.8	18.9	18.9	19.1	19.2	Volume of injected air(x)

To calculate the measurement accuracy of the device according to previous results:

- Average of measurement results:

$$\text{Mean} = \frac{19.2+19.1+18.9+18.9+18.8+18.8+18.9+18.9+19.2+18.8}{10} = 18.95\ \text{mL}$$

- Calculation of standard deviation (Hogg *et al*., 2018): $\sigma = \sqrt{\frac{\Sigma(x\text{-mean})^2}{n-1}}$

where:

n = The number of measurements (number of tests); mean = The average value of the measurement; x = Measurement value in the test n; σ = standard deviation.

After substituting into the previous equation, we find the value of the standard deviation: σ = 0.16 mL. Hence, the measurement accuracy of the device is estimated to be ±0.16 mL based on the standard deviation of the measurements and an average value of 18.95 mL.

Figure 11 represents the data from Table 2 compared with the theoretical and average values. It can be observed that the theoretical value differs from the average value of the measurement. This difference can be attributed to the decrease in the volume of gas within the bucket due to the pressure of the column of liquid (water) contained within the cell (h = 10 cm). According to Boyle's Law:

$$P_1.V_1 = P_2.V_2 \Rightarrow P_1.V_1 = (\rho_1 + \rho.g.h).V_2$$

$$V_2 = \frac{P_1.V_1}{(\rho_1+\rho.g.h)} = \frac{1.013 \times 10^5 \times 19.34}{1.013\times105\times9.81\times10\times10^{-2}} = 19.15 \text{ mL}$$

Hence, the decrease in volume caused by the pressure of the water column above the bucket is:

$$\Delta v = v_2 - v_1 = 19.34 - 19.15 = 0.2 \text{ mL}$$

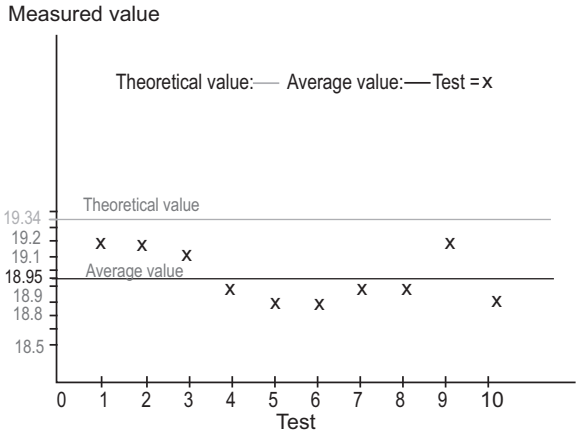

Fig. 11. A diagram representing the deviation of the measurement values from the theoretical value and the average value.

The value (19.15) represents the corrected theoretical value after considering the decrease in volume due to the pressure of the water column, and the deviation of this theoretical (corrected) value from the average (experimental) value:

$$\Delta v = 19.15 - 18.95 = 0.2 \text{ mL}$$

This deviation can be explained as follows:

- An error in the theoretical value due to an error in the measurement of the parameters that are included in its calculation, which are:

r_b = the buoyant force arm is the vertical distance between the axis of rotation passing through A and the vertical buoyant force, passing from the point of impact B; W_s = weight of the solid (the polymeric material that makes up the bucket); W_t = attachment weight (magnets) that are placed inside the bucket to aid in the measurement; r_w = the vertical distance between the axis of rotation passing through A and the vertical weight force passing through the center G (the gravity center of the bucket due to the distribution of weights within it).

- Error in the practical (experimental) value:

where it represents the average value of experimental values for a set of measurements and the deviation value of these measurements:

$$\varepsilon = x_{max}\text{-}x - x_{min} = 19.2–18.8 = 0.3 \text{ mL}$$

The reason for this deviation can be attributed to factors such as:

- Manufacturing error during making the bucket
- Bucket sensitivity to flotation
- Error in measuring gas volume by syringe

From an economic perspective, the use of renewable biogas as a source of energy is becoming increasingly important due to the need for sustainable energy sources and the mitigation of greenhouse gas emissions (Chfiumenti *et al*., 2009). The successful design and manufacture of this biogas measuring device makes it easier to monitor and optimize the biogas production process, contributing to the efficient and effective operation of anaerobic digestion systems (Fan *et al*., 2018). The real-time correction of temperature and pressure in the volume calculations can help to reduce errors and save time and costs associated with retesting and recalibration.

Accurate measurement of biogas production is crucial for studying the effect of different parameters affecting

biogas production (Rosato, 2018). This device provides a high level of accuracy (18.95 ± 0.16 mL) in measuring small volumes of gas (2-20 mL) at low pressures (close to atmospheric pressure). It is suitable for laboratory work necessary to study the volume of biogas resulting from the anaerobic digestion process. The biogas measuring device is a cost-effective and practical solution for biogas measurement, which can help to advance research in the field of anaerobic digestion and support the development of sustainable energy sources. Furthermore, the digital storage of data within a database enables easy processing and presentation of data as required, improving the efficiency and accuracy of data analysis and reducing the time and costs associated with manual data processing.

Overall, the biogas measuring device has wide applications in laboratory processes where gas volume is a standard for comparing results. Its accuracy, real-time correction of gas volume and electronic counting system make it a cost-effective and efficient solution for measuring biogas production. Some potential future directions for the biogas measuring device include integrating it with automated data analysis, while the device currently has the capability to store data in digital form, it could potentially be integrated with automated data analysis tools to provide real-time analysis of biogas production. This could enable researchers to quickly identify trends and patterns in biogas production and adjust their experiments as needed. Another future direction may involve integration it this device with other biogas measurement techniques. The device could potentially be integrated with other biogas measurement techniques, such as gas chromatography, to provide more comprehensive data on biogas composition and production rates. This could enable researchers to better understand the factors that influence biogas production and optimize their biogas production processes. There also exists a need for further improvement in accuracy and precision of this device. While the current device has a measurement accuracy of (18.95 ± 0.16 mL), there may be opportunities to improve this accuracy and precision in the future. This could involve refining the design of the device, using more precise measurement techniques, or implementing additional calibration procedures.

Scaling up the biogas measuring device for larger anaerobic digestion systems may present some challenges such as increased gas volume. As the production of biogas increases in larger anaerobic digestion systems, the gas volume that needs to be measured also increases. To scale up the device, it may be necessary to increase the size of the measurement chamber or use a different measuring principle to accommodate the higher gas volumes. Another potential challenge may involve variations in pressure and temperature: In larger anaerobic digestion systems, the pressure and temperature of the biogas may vary more widely than in laboratory-scale systems. This may require modifications to the device to ensure that pressure and temperature corrections are made accurately in real-time. This device may also be in need for more maintenance. As the device is scaled up, it may require more maintenance to ensure accurate measurements. This may include more frequent calibration, cleaning, and inspection of the measurement chamber. Lastly, the cost of scaling up the device may also be a challenge. Larger devices may require more materials and components, resulting in higher production costs.

Conclusion

The biogas measuring device designed in this research provides accurate measurement (average 18.95 mL, standard deviation 0.16 mL) (18.95±0.16 mL) and meets the requirements of laboratory work necessary to study the volume of biogas resulting from the anaerobic digestion process of a digester containing up to 1440 g of volatile fatty acid (VFA). The device features a wide gas flow measurement range (20-4000 mL/h), real-time correction of temperature and pressure in the volume calculations, and data storage capability that enables easy processing and presentation of data. The device also has low maintenance requirements and a low cost, making it a cost-effective solution for measuring biogas production in a laboratory or low gas rate application setting. The biogas measuring device's electronic counting system allows for automatic recording of the produced volume over time, providing real-time readings. For applications with minimal gas flow, a bucket with a lower capacity (e.g., 2 mL) would be appropriate for the required accuracy of measurement, as demonstrated in this research. The device corrects for changes in the temperature, pressure, and humidity of the gas produced in real-time to standard pressure (1 atm) and temperature (25 °C) conditions. This device has wide applications in laboratory processes where gas volume is a critical parameter for the comparison of results.

Nomenclature:

AH = absolute humidity (Kg/m^3); F_b = buoyant force

acting on the bucket (N); g = earth's gravitational acceleration (m/s^2); G = gravity center of the bucket; M_{H_2O} = molecular weight of water (18 g/mol); M_{H_2O} = mass of water vapour (Kg); n = number of measurements (number of tests); P_{biogas} = biogas pressure (pa); ΔP_{GM} = pressure loss of the measurement (pa); P_h = hydrostatic pressure of the liquid (pa); P_{H_2O},sat = partial pressure of water vapor in biogas (pa); r_b = buoyant force arm (m); R_{H_2O} = Gas constant of water vapour (461.52 J/Kg/K); r_w = weights force arm (m); T_{biogas} = wet gas temperature (Kelvin); V_g = volume of gas accumulated within the bucket (m^3); V_s = volume of the solid (polymeric) (m^3); V_t = volume of the attachments (magnet) (m^3); W_g = weight of the gas (Kg); W_s = weight of the solid (Kg); W_t = attachment weights (magnets) (Kg); x = measurement value in the test n; γ_w = specific weight of water (Kg/m^3); σ = standard deviation.

Conflict of Interests. The authors declare that they have no conflict of interest.

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