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Analyzing Anaerobic Digesters – What is Destroyed and What is Produced?

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Abstract. Anaerobic digesters have been and are being designed and built on dairy farms to control odors, reduce existing costs for electricity and bedding, and maybe add a revenue stream; electricity, bedding, and/or compost. What actually goes on inside an anaerobic digester; what is destroyed and what is produced? Biogas production may not be measured and reported accurately, and fixed solids need to be taken into consideration.

Keywords. Anaerobic Digesters, Gas Production, Fixed Solids

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Introduction

Anaerobic digestion is the biological conversion of volatile solids or biodegradable material to carbon dioxide [CO_2], methane [CH_4] and other trace gases in the absence of oxygen. This process is utilized for treating animal manure to reduce odor and to produce methane that can be burned in an engine to generate electricity for on-farm use and for sale to the utility.

Analysis of Anaerobic Digesters

There are two issues that need to be discussed, biogas production and mass balance of a digester. Biogas is produced during the biological breakdown of organic matter commonly equated with volatile solids. The solid material in manure is divided into several categories. One approach is:

> Total solids [TS] – that remaining after water has been evaporated at 103° C. There may be some material in a waste that will vaporize at this temperature, besides water;
>
> Volatile solids [VS] – that part of the total solids that will be burned or vaporized at 500° C. VS are generally considered to be organic matter. However, there may be some inorganic solids that vaporize at this temperature; and
>
> Fixed solids [FS] – the ash material remaining after the VS have been burned.

In addition, these same solids can be divided into other major categories such as suspended and dissolved solids.

The ratio of volatile solids to fixed solids is sometimes used to characterize the amount of organic matter present in a waste.

Fixed solids (FS) are the only fraction of the manure that remains unchanged during any biological process including anaerobic digestion. Because of this, FS can be used as a tracer – a standard for comparison. The change in the ratio of volatile solids to fixed solids [VS:FS] is a convenient way to analyze the change in volatile solids. Of course this procedure assumes that there are no fixed solids lost during the process due to settling.

Production of Biogas

The production of biogas in an anaerobic digester is often express in terms of cubic feet of gas per cow-day or cubic feet of gas per pound of volatile solids destroyed. These two numbers vary widely between and within digesters. Cubic feet per cow-day should vary directly with hydraulic retention time [HRT]; the greater the HRT the more gas should be produced per cow-day. However, cubic feet of gas per lb of VS destroyed should be independent of HRT. In fact, one pound of biogas should be produced for each pound of volatile solids destroyed. Too often, claims are made that more biogas is being produced than is theoretically possible. Why?

When determining the loss of solids during digestion via the biogas production, knowing the production of biogas and the properties of the biogas is important. The fate of the water and condensate is much less important because the mass of water in the digester is so much larger, maybe 20 times, than the solids.

Destruction of volatile solids yields a biogas composed of methane [CH_4], carbon dioxide [CO_2] and other trace gases. The gram molecular weights of CO_2 and CH_4 are 44 and 16, respectively. A biogas with a higher concentration of CO_2, though having a smaller heating value, will have a higher molecular weight and indicate in greater destruction of volatile solids.

Chemistry texts say that one-gram molecular weight of a gas will occupy 22.4 liters at standard conditions (STP) [0°C and 1 atmosphere or 0.791 ft^3 at 32°F and 1 atm]. The molecular weight of the biogas depends on the relative concentration of CO_2 and CH_4, ignoring the trace gases. Table 1 presents the properties of dry biogas for a range of CO_2 levels from 60 to 30 percent by volume and the corresponding g mol wt [gram molecular weight]. Note that the gram molecular weight decreases as the concentration of CO_2, the heaviest gas, decreases.

Tale 1. Properties of Biogas at Standard Conditions

Dry Biogas [CH_4 and CO_2] at Standard Conditions [32 F & 1 atm]					
% CO_2 by volume	g mol wt	CH_4 Percent by weight	Density lbs d.g.*/ft^3	Density ft^3/lb d.g.	HHV Btu/ft^3
60%	32.8	19.5%	0.0915	10.92	425
58%	32.2	20.8%	0.0900	11.11	446
56%	31.7	22.2%	0.0884	11.31	468
54%	31.1	23.7%	0.0868	11.51	489
52%	30.6	25.1%	0.0853	11.73	510
50%	30.0	26.7%	0.0837	11.94	531
48%	29.4	28.3%	0.0822	12.17	553
46%	28.9	29.9%	0.0806	12.41	574
44%	28.3	31.6%	0.0790	12.65	595
42%	27.8	33.4%	0.0775	12.91	616
40%	27.2	35.3%	0.0759	13.17	638
38%	26.6	37.2%	0.0743	13.45	659
36%	26.1	39.3%	0.0728	13.74	680
34%	25.5	41.4%	0.0712	14.04	701
32%	25.0	43.6%	0.0697	14.36	723
30%	24.4	45.9%	0.0681	14.69	744

* dry gas

Because the heat energy in the biogas is from burning the methane, the percent methane by weight is given. The heating value for the biogas at various concentrations of CO_2 is given in the right column. Because this is dry gas, the heating value is considered to be the high heating value (HHV).

The density [lb d.g./ft^3] and volume [ft^3/lb d.g.] of the biogas at standard conditions are presented. Theoretically, one pound of biodegradable organic matter or volatile solids would be destroyed producing one pound of dry biogas. Again, note that the pounds of volatile solids destroyed per cubic foot of biogas produced decreases as the carbon dioxide concentration decreases.

The volume of biogas measured at a gas meter will be dependent on the temperature, the pressure of the gas and moisture content. There are gas meters that are temperature compensated but it is doubtful that most gas meters used on digesters do not have temperature compensation. The impact of gas temperature on the density of biogas with 40% CO_2 and saturated at 1 atm is shown in Figure 1. The density of the biogas at standard temperature and pressure (STP) is shown. This is a dry biogas. The remaining plotted points are for biogas saturated with water vapor.

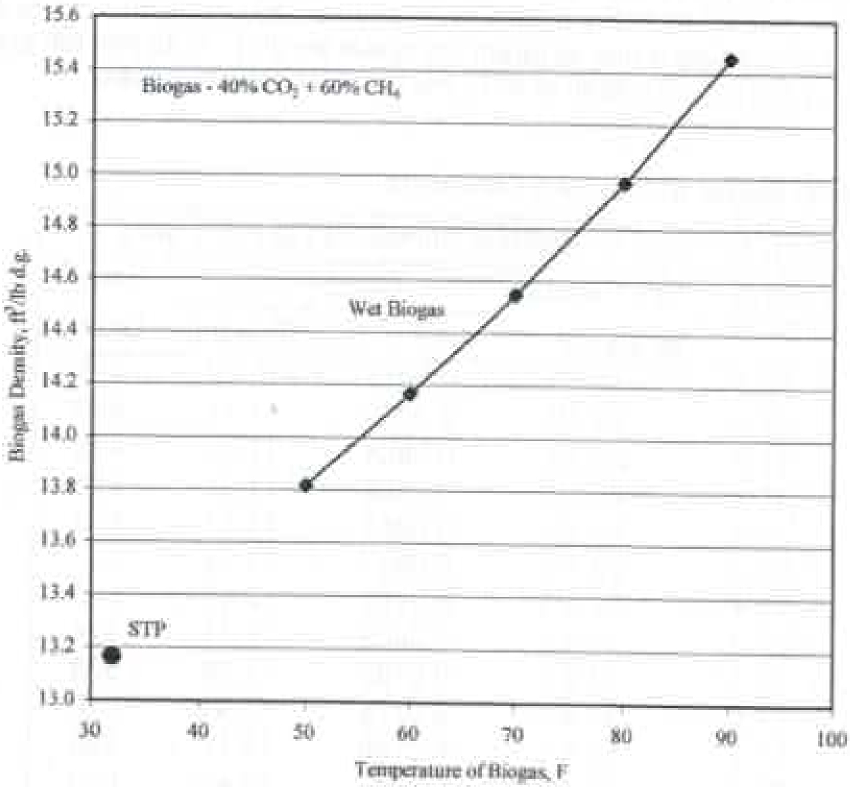

Figure 1. Relationship Between Gas Temperature and Density of Biogas

The relationship for gases at various temperatures, pressures and saturated with water vapor is given by the familiar equation shown below. The assumption is made that the biogas escaping from the surface of the digesting liquid will be composed of CH_4, CO_2, and water vapor, and is at the temperature of the digester.

$$\frac{760 \times V_{STP}}{273^{\circ} A} = \frac{(760 - PP_{water}) \times V_2}{T_2}$$

Where: 760 mm Hg [1 atmosphere], 273° A [0° C] and V_{STP} are at standard conditions.

PP_{water} is the partial pressure [mm Hg] of water vapor at temperature T_2, V_2 is the volume of the wet gas at T_2, with T_2 is in degrees absolute. Partial pressures for water vapor at various temperatures are shown in a table in the Appendix.

Other gases such as H_2S will be present in small amounts. These will not be considered here. The biogas leaving the digester will probably be at a lower temperature than the main digester but still saturated. Depending on the piping and distance to the gas meter, the biogas will continue to drop in temperature and water vapor will condense. This condensate will either drain back to the digester or to a water trap. Because the amounts are small, this will not be considered here.

The properties of biogas at various concentrations of CO_2 at 90°F are given in Table 2. For reference, tables for temperatures of 80, 70, 60 and 50 °F are given in the Appendix.

As stated earlier, the anaerobic digestion of one (1) pound of volatile solids will yield one pound of dry biogas. Table 2 shows the pounds of volatile solids destroyed per 1,000 ft^3 of wet biogas produced at 90 F. The weight removed from the digester [dry biogas plus water of saturation] for each 1,000 ft^3 of wet biogas is also given along with the high and low heating values.

Perhaps biogas production should be expressed in terms of lbs biogas with a concentration of CO_2 or lbs of CH_4 per cow-day. If volume is chosen, a standard temperature and pressure should be set.

Table 2. Properties of Biogas at 90 F and 1 Atmosphere

Biogas - Water Vapor Saturated [90 F and 1 atm]						
% CO2 by volume	ft^3/lb d.g.	VS Destroyed lbs d.g./ 1,000 ft^3	HHV Btu/ft^3	Moisture lbH_2O/lb d.g.	Weight Removed lbs/1000ft^3	LHV Btu/ft^3
60%	12.82	78.0	362	0.031	80.4	330
58%	13.04	76.7	380	0.031	79.0	348
56%	13.27	75.3	398	0.031	77.7	366
54%	13.51	74.0	417	0.031	76.3	384
52%	13.76	72.7	435	0.031	74.9	402
50%	14.02	71.3	453	0.031	73.5	421
48%	14.28	70.0	471	0.031	72.2	439
46%	14.56	68.7	489	0.031	70.8	457
44%	14.85	67.3	507	0.031	69.4	475
42%	15.15	66.0	525	0.031	68.1	493
40%	15.46	64.7	543	0.031	66.7	511
38%	15.79	63.3	561	0.031	65.3	529
36%	16.13	62.0	580	0.031	63.9	547
34%	16.48	60.7	598	0.031	62.6	565
32%	16.85	59.4	616	0.031	61.2	583
30%	17.24	58.0	634	0.031	59.8	602

HHV – high heating value, LHV – low heating value

Mass Balance on a Digester

Conducting a mass balance on a digester is extremely difficult because of the challenge of measuring mass flow, influent and effluent, of the digester and the challenge of obtaining representative samples of the influent and effluent for analysis. A digester should be a "sealed" vessel with a waste influent, an effluent, and a biogas stream. The mass of the influent should equal the combined mass of the effluent and biogas (CO_2, CH_4 and water vapor) assuming there is no settling; M-Influent = M-Effluent + M-biogas + Settled Solids. See Figure 2.

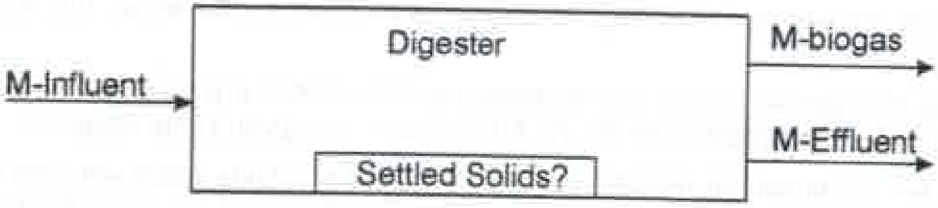

Figure 2. Schematic Flow Diagram of an Anaerobic Digester

Example of a Mass Balance

A fixed film anaerobic digester has been operating on a 100-cow dairy farm in E. Jewett, NY for three years. The insulated vertical precast concrete digester is10.5 ft inside diameter with a fluid depth of 12 ft giving a volume of about 7,800 gallons. The hydraulic retention time [HRT] was designed for 4 days. Only the liquid fraction from the separator is digested. Data on gas production, digester temperatures and gas analysis were collected daily. Analysis of the digester influent and effluent were conducted periodically, 12 tests over a period of 323 days. The resulting data is given in Table 3. Analysis of the biogas showed an average CO_2 concentration of 37%. The temperature of the biogas entering the gas meter was not measured. The temperature was assumed to average 60 °F. This combination of properties gave a weight loss from the digester of 69 lbs/1000 ft^3.

Table 3. Farm 1 – Mass Balance

Parameter	Influent		Effluent		Change
	Percent	Lbs/day	Percent	Lbs/day	Lbs/day
Weight		13,920		13,760	-163*
Total Solids	4.9	676	7.75	520	-156
Volatile Solids	67.7	458	74.31	333	-125
Fixed Solids	32.3	218	25.69	186	-32

*Biogas production: 23 cuft/cow-day x 95 cows = 2,185 cuft/day

@ 69 lbs/1,000 cuft, weight loss = 163 lbs/day

Gas Production [cuft/lb VS "lost"] = 2,185/125 = 17.5

The volatile solids lost were calculated to average 125 lbs per day with 32 lbs of fixed solids remaining in the digester. The digester operated for over 500 days which means that some 16,000 lbs of fixed solids had accumulated in the digester. When the digester was opened, there appeared to be at least that amount of $CaCO_3$ and other fixed solids at the bottom of the digester and clinging to the fixed film support media [vertical section of corrugated drain pipe]. There was so much $CaCO_3$ attached to the fixed film that the support media had to be removed.

This accumulation would not have come as a surprise had attention been paid to this loss of fixed solids. There is always the thought that there must be a mistake in the analysis to explain this loss. However, when the results from all 12 tests show a loss, there probably are solids settling inside the digester.

The production of biogas at the rate of 17.5 ft^3/lb of VS lost is too high. Either the VS loss is being under estimated or the cubic feet of biogas produced is somehow being "over estimated." If some of the VS are settling then the VS lost has been over estimated. However some of these settled volatile solids will continue to biodegrade and produce biogas. There are two hydraulic retention times [HRT] active in an anaerobic digester. The common HRT deals with the liquid, generally calculated by dividing the volume of the liquid in the digester by the daily loading. If there are settled solids, made up of fixed and volatile solids, these solids will have a much longer "HRT".

The temperature of the biogas entering the meter needs to be monitored so that a more accurate measure of gas flow is possible. If digesters are to be compared, the gas production should be reported at standard temperature and temperature or reported as production in terms of mass instead of volume along with gas composition.

A mass balance on two other anaerobic digesters was conducted. The results are given below in Tables 4 and 5.

The digester at Farm 2 has an HRT of 40 days. Based on the analysis of 9 samples, 80 lbs per day of fixed solids are not accounted for and presumed to be in the digester. This means that

Table 4. Farm 2 – Mass Balance

Parameter	Influent		Effluent		Change
	Percent	Lbs/day	Percent	Lbs/day	Lbs/day
Weight		91,700		88,900	-2,800*
Total Solids	11.42	10,470	8.30	7,380	-3,090
Volatile Solids	84.15	8,810	78.65	5,800	-3,010
Fixed Solids	15.85	1,660	21.35	1,580	-80

*Biogas production: 85 cuft/cow-day x 500 cows = 42,500 cuft/day

@ 66 lbs/1,000 cuft, weight loss = 2,800 lbs/day

Gas Production [cuft/lb VS "lost"] = 42,500/3,010 = 14.1

nearly 12 tons of fixed solids [dry matter] accumulates each year. The 85 ft^3 per cow-day seems high even with a 40 day HRT. The gas production of 14 ft^3 per lb of VS "lost", based on an assumed temperature and gas composition, was certainly within reason but this could be due to an inflated biogas production.

Farm 3 has 850 milking cows and an anaerobic digester with a HRT of about 21 days. The data in Table 5 was based on 18 samples over a period of 2.5 years. The fixed solids that are unaccounted for should be of concern. With 18 analysis dates showing an average of 190 lbs of fixed solids [dry] accumulating, this means nearly 35 tons of dry matter per years could be settling in the digester. The 11 ft^3 of biogas produced per pound of VS "lost" is not possible. This is another warning sign that some volatile solids may remain in the digester thus inflating the volatile solids destroyed or there is an error in measuring the biogas produced.

Table 5. Farm 3 - Mass Balance

Parameter	Influent		Effluent		Change
	Percent	Lbs/day	Percent	Lbs/day	Lbs/day
Weight		141,800		139,500	-2,300*
Total Solids	9.01	12,780	6.75	9,420	-3,360
Volatile Solids	82.88	10,590	78.77	7,420	-3,170
Fixed Solids	17.12	2,190	20.28	2,000	-190

*Biogas production: 41 cuft/cow-day x 850 cows = 34,850 cuft/day

@ 66 lbs/1,000 cuft, weight loss = 2,300 lbs/day

Gas Production [cuft/lb VS "lost"] = 34,850/3,170 = 11

The accuracy of conventional gas meter is being questioned when used with wet biogas. Gas meters using other technologies to measure gas flow or velocity should be investigated. With so much emphasis being paid to gas production, accurate measurement is essential.

Conclusions

Closer analysis of the results from tests conducted on the influent, effluent, and biogas along with mass flows can uncover issues that need be explored further. Better data on the production of biogas and the potential for solids settling in the digester can be of help in judging how a digester is really operating.

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Appendix

VAPOR PRESSURE OF WATER
EXPRESSED IN MILLIMETERS OF MERCURY
(from International Critical Tables)

Temp F	Pressure
50	9.209
55	11.073
60	14.666
65	15.807
70	18.779
75	22.233
80	26.234
85	30.827
90	36.118
95	42.175

Biogas - Water Vapor Saturated [80 F, 1 atm]

% CO2 by volume	ft^3/lb d.g.	VS Destroyed lbs d.g./ 1,000 ft^3	HHV Btu/ft^3	Moisture lbH_2O/lb d.g.	Weight Removed lbs/1000ft^3	LHV Btu/ft^3
60%	12.42	80.5	374	0.0223	82.3	351
58%	12.64	79.1	393	0.0223	80.9	369
56%	12.86	77.8	411	0.0223	79.5	388
54%	13.09	76.4	430	0.0223	78.1	407
52%	13.33	75.0	449	0.0223	76.7	425
50%	13.58	73.6	467	0.0223	75.3	444
48%	13.84	72.3	486	0.0223	73.9	463
46%	14.11	70.9	505	0.0223	72.5	482
44%	14.39	69.5	523	0.0223	71.1	500
42%	14.68	68.1	542	0.0223	69.7	519
40%	14.98	66.8	561	0.0223	68.2	538
38%	15.29	65.4	579	0.0223	66.8	556
36%	15.62	64.0	598	0.0223	65.4	575
34%	15.97	62.6	617	0.0223	64.0	594
32%	16.32	61.3	636	0.0223	62.6	612
30%	16.70	59.9	654	0.0223	61.2	631

Biogas - Water Vapor Saturated Gas [70 F and 1 atm]						
% CO2 by volume	ft^3/lb d.g.	VS Destroyed lbs d.g./ 1,000 ft^3	HHV Btu/ft^3	Moisture lbH_2O/lb d.g.	Weight Removed lbs/1000 ft^3	LHV Btu/ft^3
60%	12.06	82.9	385	0.016	84.2	368
58%	12.27	81.5	404	0.016	82.8	388
56%	12.49	80.1	423	0.016	81.3	407
54%	12.71	78.7	443	0.016	79.9	426
52%	12.95	77.2	462	0.016	78.5	445
50%	13.19	75.8	481	0.016	77.0	465
48%	13.44	74.4	500	0.016	75.6	484
46%	13.70	73.0	520	0.016	74.2	503
44%	13.97	71.6	539	0.016	72.7	522
42%	14.25	70.2	558	0.016	71.3	542
40%	14.55	68.7	577	0.016	69.8	561
38%	14.85	67.3	597	0.016	68.4	580
36%	15.17	65.9	616	0.016	67.0	599
34%	15.50	64.5	635	0.016	65.5	619
32%	15.85	63.1	654	0.016	64.1	638
30%	16.22	61.7	674	0.016	62.7	657

Biogas - Water Vapor Saturated [60 F, 1 atm]						
% CO_2 by volume	ft^3/lb d.g.	VS Destroyed lbs d.g./ 1,000 ft3	HHV Btu/ft^3	Moisture lbH_2O/lb d.g.	Weight Removed lbs/1000ft3	LHV Btu/ft^3
60%	11.75	85.1	395	0.011	86.0	384
58%	11.96	83.6	415	0.011	84.6	403
56%	12.17	82.2	435	0.011	83.1	423
54%	12.39	80.7	454	0.011	81.6	443
52%	12.61	79.3	474	0.011	80.2	463
50%	12.85	77.8	494	0.011	78.7	483
48%	13.09	76.4	514	0.011	77.2	502
46%	13.35	74.9	533	0.011	75.7	522
44%	13.61	73.5	553	0.011	74.3	542
42%	13.89	72.0	573	0.011	72.8	562
40%	14.17	70.6	593	0.011	71.3	581
38%	14.47	69.1	613	0.011	69.9	601
36%	14.78	67.7	632	0.011	68.4	621
34%	15.10	66.2	652	0.011	66.9	641
32%	15.44	64.8	672	0.011	65.5	660
30%	15.80	63.3	692	0.011	64.0	680

Biogas - Water Vapor Saturated [50 F, 1 atm]						
% CO2 by volume	ft^3/lb d.g.	VS Destroyed lbs d.g./ 1,000 ft^3	HHV Btu/ft^3	Moisture lbH_2O/lb d.g.	Weight Removed lbs/1000ft^3	LHV Btu/ft^3
60%	11.46	87.2	405	0.0076	87.9	397
58%	11.66	85.7	425	0.0076	86.4	417
56%	11.87	84.3	446	0.0076	84.9	438
54%	12.08	82.8	466	0.0076	83.4	458
52%	12.30	81.3	486	0.0076	81.9	478
50%	12.53	79.8	506	0.0076	80.4	498
48%	12.77	78.3	527	0.0076	78.9	519
46%	13.02	76.8	547	0.0076	77.4	539
44%	13.28	75.3	567	0.0076	75.9	559
42%	13.54	73.8	587	0.0076	74.4	579
40%	13.82	72.3	608	0.0076	72.9	600
38%	14.11	70.9	628	0.0076	71.4	620
36%	14.42	69.4	648	0.0076	69.9	640
34%	14.73	67.9	668	0.0076	68.4	661
32%	15.06	66.4	689	0.0076	66.9	681
30%	15.41	64.9	709	0.0076	65.4	701