

Pump Performance Tests as a Method of Determining Influent Mass Flows to Dairy Farm Anaerobic Digesters

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Abstract

A new on-farm anaerobic digester (AD) monitoring protocol, recently released by the Association of State Energy Research Technology and Transfer Institutions (ASERTTI) is being used to assess seven anaerobic digesters on dairy farms in New York State. A key component of the ASERTTI protocol is to perform a mass balance of the AD system. Mass balance data is needed to determine system performance values such as: degree of manure stabilization, biogas produced per unit of influent, and subsequent electrical power produced per unit of influent. The optimal location in the system to obtain AD influent mass flow data is at the AD influent pump. However, pumps used to pump manure generally lack performance data, making it difficult to quantify mass flow without knowing the performance characteristics of the influent pump.

In order to determine in-place pump performance, field tests were conducted on each of the two types of influent pumps used on the farms: centrifugal pumps and hydraulic piston pumps. The performance test for the hydraulic piston pump consisted of pumping AD influent to a separate vessel while counting the number of pump strokes; the wet weight per stroke was then determined. The pump test for the centrifugal pump consisted of filling the AD influent pit and then pumping the contents to the AD while measuring the change in depth of the pit every ten minutes throughout the test to determine the average flow rate for the dynamic pump head.

To date, pump calibration tests have been performed on five of the seven farms. Volumetric efficiencies for four of the hydraulic piston pumps were found to be on average 91, 64, 83 and 57 percent based on three separate trials at each farm, pumping on average about 5,000 gallons per trial. Manure density tests performed the day of the pump performance evaluation resulted in specific gravities of 1.02, 1.01, 1.02 and 1.02, with respect to the efficiencies listed above. Average flow rates for two centrifugal pumps tested at one farm were found to be 381 gpm and 564 gpm.

Keywords: Anaerobic digestion, renewable energy, manure treatment, centrifugal pump, hydraulic piston pump

Introduction

Anaerobic digestion of farm-based biomass has received a great deal of attention in the recent past and this interest has increased significantly most recently due to societal concerns of rising fossil fuel prices, greenhouse gas emissions, and renewable energy interests. These and other environmental issues have resulted in the construction of several New York State on-farm anaerobic digesters in the last six years, with comparatively more in the planning stages, scheduled for construction, or currently under construction.

Some of the existing anaerobic digesters in the U.S. have been monitored and reported on in the past, and each investigator has developed his or her own monitoring methodology to follow since there was previously no standard or protocol established. Therefore, published reports were not necessarily useful to make comparisons between monitored systems. In January of 2007, the Association of State Energy Research Technology and Transfer Institutions (ASERTTI) released a protocol for monitoring on-farm anaerobic digesters. The ASERTTI protocol requires quantification of many items, including anaerobic digester (AD) influent and effluent mass flow rates. The measured mass flow rates, along with analytical data obtained from field sample analysis is used to determine the mass of key constituents entering and exiting the AD. The key constituents vary depending on the scope of the monitoring project, but for all systems include the total solids (TS) and volatile solids (VS) entering and leaving the AD. Of particular interest and necessity is the VS concentration for the influent and effluent masses; a portion of the VS are consumed by AD operative microbes which in turn produce biogas.

Cornell University is currently monitoring seven New York State on-farm dairy manure based anaerobic digester systems following the ASERTTI protocol. Five of the systems are dairy manure based (AA, NHV, NH, SK, EM) and two are dairy manure blended with food waste (PAT, RL) anaerobic digesters. The purpose of this paper is to present and discuss the AD influent mass flow quantification work performed to date and provide information about how this is being accomplished in the field.

Literature Review

Pumps are designed to operate at the “point of best efficiency” (Karassik, 1976). However, there are several factors that affect pump performance and ultimately decrease the level of efficiency during operation. The volumetric efficiency is characterized by the ratio of actual delivery to ideal delivery for piston pumps (Wilson, 1950). The flow in a centrifugal pump varies according to total dynamic head while theoretically, the flow in a positive displacement pump is not affected by changes in head (Karassik, 1976).

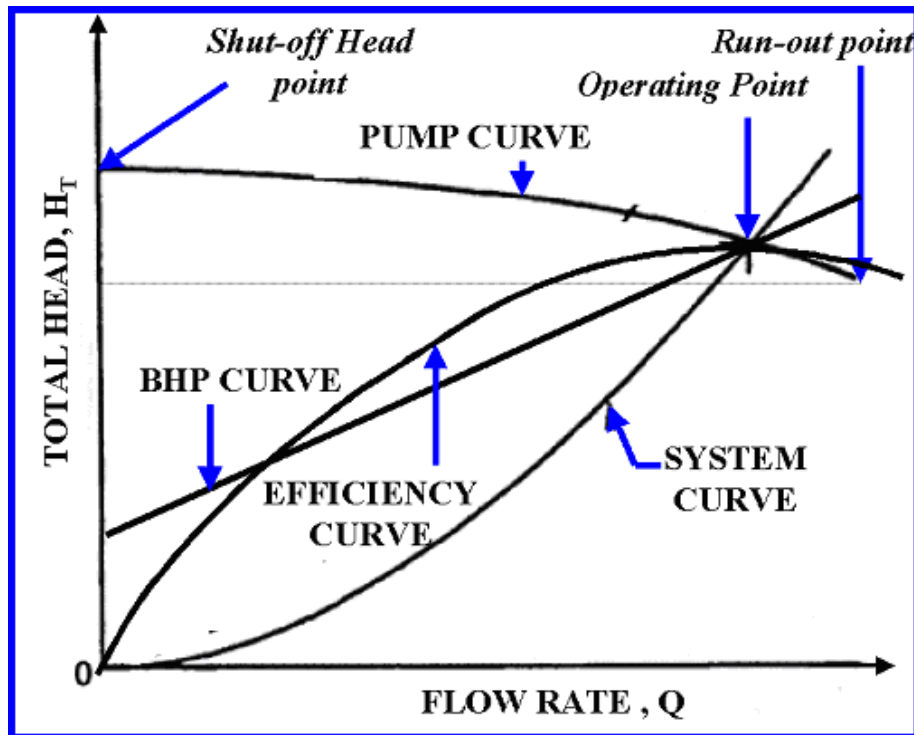


Figure 1. Typical system and pump performance curves (CHE Resources, 2008)

The graph above shows a typical centrifugal pump curve. The intersection of the pump curve and the system curve represents the point of best efficiency for any specific centrifugal pump. The pump curve shows that as the flow rate increases in the pipe, so does the friction between the material and the pipe – this friction reduces the flow rate. The pump curve shows that the higher the head, the lower the flow rate (Karassik, 1976).

After an extensive literature search for reports on dairy manure based pump performance testing or calibration, no reports were discovered. Any direction to previous findings or reports on this topic would be helpful for future pump performance tests; the authors would welcome any undiscovered reports on this topic.

Background

Experience gained from previous AD monitoring projects has shown and confirmed that obtaining good quality influent and effluent mass flow data is neither easy nor straightforward to accomplish. In most cases, there is no pump performance data (pump curves) available from pump manufacturers for pumping manure. Even if there was, rarely is the manure being pumped homogenous from the beginning of any particular pumping episode to the end of that episode, nor are the manure properties that affect pump performance, most notably TS content, necessarily consistent from day-to-day. This variance is observed in the results of a previous monitoring study of five on-farm AD systems in New York State, presented in Table 1, which show the range of values for TS content of AD influent (Gooch and Inglis, 2006).

Table 1. Influent percent TS concentration for five farms

Constituent	Farm	AA	DDI	FA Fixed- Film	FA Vertical Plug- Flow	ML Manure	ML Food Waste	ML Calculated Influent	NH
	Statistic								
TS (percent)	Ave	11.15	9.81	4.96	5.36	13.06	26.1	15.5	10.4
	St. Dev.	1.24	1.55	0.42	0.65	4.16	18.7	8.21	2.29
	CI	0.28	0.58	0.21	0.18	1.60	7.34	4.31	0.98
	n	75	28	15	52	26	25	24	21

Another challenge in obtaining reliable influent and effluent mass flow data is the presence of manure constantly entering the pump pit during field performance evaluation of the pump or during subsequent pump monitoring. Cows continuously produce manure, on average 150 lbs/cow-day (ASABE, 2005), and this manure along with any other AD pump influent continues to flow to the pit during pump testing. The inability to stop this flow makes it difficult, if not completely impossible in some cases, to determine the volume (mass) pumped by measuring the difference in pump influent pit manure volume at the beginning and end of the test.

Pump performance characteristics must be known in order to accurately quantify the mass of influent transferred to the AD by the influent pump. To ascertain the pump efficiency for the influent pump, a pump performance test has been performed on five of the seven farms. Quantification of AD influent will help later when calculating the biogas produced per unit of influent, and subsequently, the electrical power produced per unit of influent.

The seven farms use one of two types of pumps to transfer influent to the AD: hydraulic piston and centrifugal. Influent may consist of any or all of the following: dairy cow manure, used bedding, milking center wastewater, solid-liquid separator liquid effluent, and on the farms using centrifugal pumps, food waste co-substrates. The first step was to assess the different pump set-ups at each farm to determine the best way to perform the calibration. A methodology was developed for each type of pump, and although challenges were encountered for each system, the basic methods prevailed. As previously mentioned, this portion of the AD system cannot be isolated; all of the pumps undergoing calibration were previously installed and continued operating during the interval of testing.

Table 2 summarizes the characteristics of the pumping system at each farm monitored.

Table 2. Pump and agitator information for five farms

	Farm	AA	NHV	PAT	SK	EM
AD Influent pump	Type	Piston	Piston	Centrifugal	Piston	Piston
	Year installed ^A	1998	2001	2005	2006	2006
	Make	Houle	Houle	Houle	Houle	Houle
	Model #	<u>00-653 P-E-7.5</u>	<u>1102-01653-7.5</u>	<u>0806-050885-121610</u>	<u>1102-05099-85</u>	NA
	Motor Size (Hp)	7.5	7.5	10	7.5	NA
	Bore & Stroke	19" 46 ¼"	19" 46 ⅝"	NA	19" 38"	19" 46.875"
AD influent pit agitator	Make	Houle Impeller	Houle Impeller	Houle Impeller	Houle Impeller	Houle Impeller
	Motor size (Hp)	7.5	10	20	10	10
Performance testing date	10/24,25/2007 & 4/22/2008	10/10/07	10/27/07	9/6/07	10/30/07	

^AThe assumption was made that the year of installation is the same year as the commissioning of the farm's AD system

Materials and Methods

Hydraulic Piston Pumps

In theory, a well-designed and maintained hydraulic piston pump will transfer the same volume of manure per stroke, if the properties of the manure are constant. The theoretical volume of manure pumped per stroke is a function of the bore diameter (d) multiplied by the stroke length (l), as shown in Equation 1. The total volume of manure pumped is the volume per stroke multiplied by the number of strokes. During the pump performance tests, measurements including inside bore diameter (d) and stroke length (l) were recorded and used to calculate the theoretical volume of manure pumped.

$$V = \pi \times \left(\frac{d}{2}\right)^2 \times l \quad (1)$$

However, this method assumes the bore volume is completely filled with manure during the suction phase of the pumping cycle. If the bore volume is not completely filled, then the actual manure pumped is less than theoretical, resulting in over-prediction of the daily influent to the

AD. Thus, the volumetric efficiency of each pump was quantified (shown later in Equation 6) to determine the percentage of theoretical bore volume transferred per stroke.

The methodology used for farms with hydraulic piston pumps, to ultimately determine the daily influent total mass pumped to the AD, was to first determine the mass transferred per pump stroke and then use project-installed stroke counters to determine the AD influent mass for the period of time between project-scheduled site visits.

For the hydraulic piston pumps, found on four of the farms, the pump effluent stream (AD influent) was diverted to fill an 8,000 gallon manure tanker (typically used as a nurse tank during manure spreading operations) as shown in Figure 1. Concurrently, the number of pump strokes was counted.



Figure 2. Pump test setup at SK

The AD influent pit impeller agitator was run at least 10 minutes prior to, and then throughout the remainder of the pump performance test. The tanker was weighed before and after being filled using each farm's truck scales, and the tare weight (weight of tanker prior to filling) as well as the loaded weight (weight after filling the tanker) were recorded. The difference between the tare weight and loaded weight represents the weight of manure pumped. Three

trials were performed at each site on the same day (except AA¹), and the data was used to calculate the wet weight of AD influent per stroke, using Equation 2 for each trial.

$$\frac{\text{weight}}{\text{stroke}} = \frac{\text{total manure pumped (lbs)}}{\text{total \# pump strokes}} \quad (2)$$

Another component of the pump performance test was to obtain the manure specific gravity in order to calculate the volumetric pump efficiency for each pump on each farm, and to compare specific gravities of AD influent at each farm. For both the hydraulic piston pumps and the centrifugal pumps, a five gallon bucket was filled several times (actual number of times varied by site) with each farm’s potable water to obtain the unit volume weight of the reference liquid – in this case, fresh water. Specific gravity is a unit-less ratio of the specific weight of a liquid (in this case manure) to the specific weight of a reference liquid (usually water) (AIChE, 1960). The bucket is then filled full to the brim with manure and leveled off several times to get an average reading of the unit volume weight of the manure. The specific gravity was determined using the two measured values in Equation 3.

$$\text{Specific gravity} = \frac{\text{Average unit volume weight manure}}{\text{Average unit volume weight water}} \quad (3)$$

Specific gravity is used to calculate the volume of manure (ft³) pumped, as shown in Equation 4.

$$\text{manure pumped (ft}^3\text{)} = \text{manure pumped (lbs)} \times \frac{1 \text{ ft}^3}{62.4 \text{ lbs}} \times \frac{1}{\text{manure specific gravity}} \quad (4)$$

¹At AA, trials were performed over 3 different days due to foreign objects clogging the influent pipe; see “Results” section for more details.

The result of the previous calculation divided by the number of pump strokes counted gives the volume per stroke ($\text{ft}^3/\text{stroke}$) as shown in Equation 5.

$$\text{Volume per stroke}(\text{ft}^3 / \text{stroke}) = \frac{\text{manure pumped} (\text{ft}^3)}{\text{number pump strokes}} \quad (5)$$

Using the value for volume per stroke, this measured value is compared to the theoretical value of the bore volume shown in Equation 1 – this comparison will determine the volumetric pump efficiency, shown in Equation 6.

$$\text{Pump efficiency} (\%) = \frac{\text{ft}^3 / \text{stroke}}{\text{calculated bore volume}} \times 100 \quad (6)$$

Centrifugal Pumps

For the farm with a centrifugal pump used in the influent pit, the methodology used to ultimately determine the daily influent total wet mass pumped to the AD was to initially determine the average pump capacity in gallons per minute (gpm) for the range of total head the pump is pumping against. The pump run time will be monitored using time clocks installed on the load side of each pump's motor starter. The time clock will be used to record the pump run time for the period of time between project-scheduled site visits. The accumulated run time (minutes) multiplied by the pump's measured average flow rate (gallons per minute) provides the total volume pumped to the AD between scheduled visits.

The AD influent pump pit width and length were measured and recorded and used to calculate the pit's horizontal cross-sectional area. The gallons per linear foot of pit depth were determined, using Equation 7. This value will be used to determine the gallons pumped per unit of time, by using measurements of the change in depth (ft) taken throughout the trial.

$$\frac{\text{gallons}}{\text{ft}} = \text{area} (\text{ft}^2) \times \frac{7.48 \text{ gallons}}{\text{ft}^3} \quad (7)$$

The AD influent pit containing the influent pump to be tested was filled to capacity with AD influent (manure and food waste), just before the point of overflow. At this maximum capacity, the distance from the top of the pit to the free surface was measured and recorded. The agitator was run at least ten minutes prior to and then throughout the remainder of the

pumping trial. The pump was then activated to begin transfer of influent to the AD. The pumping trial was timed and at each ten minute increment throughout the trial, the change in depth from the top of the pit to the free surface of the pit contents was measured and recorded.

Using the data collected as described above, the flow rate (gpm) was calculated using Equation 8 below.

$$\text{Flow rate (gpm)} = \Delta \text{ in depth (ft)} \times \frac{\text{gallons}}{\text{foot}} \times \frac{1}{10 \text{ min}} \quad (8)$$

This flow rate was calculated for each 10 minute interval during the performance test using recorded changes in depths for each interval. These flow rates were averaged to determine an overall average flow rate for the depth normally present in the AD influent pit.

Results

The most important measured and calculated values for each farm with a hydraulic piston pump are shown in Table 3 and for the farm with a centrifugal pump, values are shown in Table 4.

Table 3. Measured and calculated values for farms with piston pumps

Farm	NHV	EM	SK	AA
Number of pumping trials (n)	3	3	3	4
Theoretical bore volume (ft ³)	7.568	7.691	6.235	7.589
Total manure pumped (lbs)	45,513	70,580	51,450	30,567
Average No. of pump strokes per trial	114	159	203	124
Average time to complete one pump cycle (seconds)	20.2	24.9	12.5	46.8
Weight per stroke (lbs/stroke)	398	444	252	273.6
Calculated volume per stroke (ft ³ /stroke)	6.26	6.98	4.00	4.29
Total solids (TS) content (%) ¹	7.77	9.99	11.13	9.83
No. of weight determination trials (n)	6	4	6	8
Average manure specific gravity	1.02	1.02	1.01	1.02
Average volumetric efficiency (%)	83	91	64	57

¹The total solids values in the table are the average of one sample analyzed in triplicate

Table 4. Calculated values for the farm with a centrifugal pump

Farm	PAT	
	AD influent pit pump	Mixed pit pump
Cross-Sectional Area (ft²)	696	676
Gallons/foot	5,206	5,059
Pumping Time (minutes)	120	120
Overall change in depth (in)	107	109
Flow Rate (gpm)	564	381

Difficulties were encountered with one of the performance trials at AA. After one successful trial it was discovered during the course of conducting the second trial that a foreign object had wedged the pump foot valve open. Unaware this had been happening for some time, pump strokes were continually counted until it was observed that no manure was being pumped. Since it is unknown when the manure stopped transferring to the tanker during the course of the trial, this trial's data was removed from the data set. The remainder of the test was not performed due to the maintenance required on the pump, and the performance test was rescheduled. The data for the successful trials (1, 3 and 4) are included in the results presented in this paper.

To date, two pumps at one of the three farms using AD influent centrifugal pumps have been performance evaluated. The evaluation tests for the other two farms have been scheduled and the results will be analyzed in the following months, so that the results may be presented at the 2008 ASABE annual meeting in Providence, RI.

Discussion

For the four farms where piston pump performance tests were performed, the volumetric efficiencies found varied significantly between farms. There are several explanations for this variance; one reason is the time it takes to complete one pumping cycle. There is a difference of 36 seconds between the highest and lowest pumping times. Although there does not seem to be a direct correlation between this value and the volumetric efficiencies, it may nonetheless

have an impact. Another reason to explain the large difference in volumetric efficiencies is simply the age and length of operation of the pump. The oldest pump in this data set does show the lowest efficiency, but comparatively, not by much. Lastly, the solids content could be assumed to have an effect on the pump performance due to the impact solids have on viscosity. Again, there is no correlation displayed here, but it would be assumed that viscosity is related to pump performance.

In the case of calibrating the centrifugal pumps, extreme care was taken for all measurements since only one trial is able to be performed due to lack of a continuously flowing system. Having only one trial's worth of data increases the chances for error, whereas the piston pump trials have an average over three trials to decrease this margin of potential error.

Future Implications

Since the performance of the pump calibration tests, each pump calibrated has been outfitted with either a time clock or a bail counter, depending upon the type of pump. All hydraulic AD influent piston pumps have been outfitted with a bail counter (Redington Model 1-4615) as shown in Figure 3, to count the number of strokes. This number is recorded daily by the farms on project-prepared log sheets and also bi-weekly during scheduled site visits.



Figure 3. Installed stroke counter on a piston pump

All centrifugal pumps have been outfitted with time clocks (Redington Model 722-0004), connected to the motor starter as shown in Figure 4 to measure the pump run-time of the pump feeding the AD. This number is recorded daily by the farms on project prepared log sheets and also bi-weekly during scheduled site visits.



Figure 4. Time clock installed on a motor starter of a centrifugal pump

Conclusions

In order to know the mass flow transferred to the AD in each of these systems, the volumetric efficiency of the pump transferring that mass is a vital component to the calculation. To determine the quantity of mass flow to the AD, a pump performance test was performed for piston pumps on four farms and two centrifugal pumps on one farm. The volumetric efficiencies for the piston pumps tested were 91, 64, 83 and 57 percent, and the flow rates for the centrifugal pumps tested were 381 gpm and 564 gpm. These performance tests demonstrated highly variable results in terms of pump performance, which affects the quantification of mass flowing to the AD.

Over the next 12 months, the pump run-time or number of pump strokes for the centrifugal and piston pumps, respectively, will be recorded and used in conjunction with the volumetric efficiencies calculated in these pump calibration trials, to provide a better estimate of the mass flow to the AD. Knowing an accurate value for the mass flow into the AD system is helpful in determining the fate of this mass as it is digested to produce biogas and subsequent electrical

power and will also allow for more exact calculations of the mass of key constituents entering and exiting the AD system.

NOTICE

This report was prepared by Curt Gooch P.E., and Jennifer Pronto in the course of performing work contracted for and sponsored by the New York State Energy Research and Development Authority (hereafter "NYSERDA"). The opinions expressed in this report do not necessarily reflect those of NYSERDA or the State of New York, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it. Further, NYSERDA, the State of New York, and the contractor make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any processes, methods, or other information contained, described, disclosed, or referred to in this report. NYSERDA, the State of New York, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

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