0273-2289/95/5152—0155$05.60

Horsepower Requirements for High-Solids Anaerobic Digestion

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ABSTRACT

Improved organic loading rates for anaerobic bioconversion of cellulosic feedstocks are possible through high-solids processing. Additionally, the reduction in process water for such a system further improves the economics by reducing the overall size of the digestion system. However, mixing of high-solids materials is often viewed as an energy-intensive part of the process. Although the energy demand for high-solids mixing may be minimized by improving the agitator configuration and reducing the mixing speed, relatively little information is available for the actual horsepower requirements of a mechanically mixed high-solids digester system.

The effect of sludge total solids content and digester fill level on mixing power requirements was evaluated using a novel NREL laboratory-scale high-solids digester. Trends in horsepower requirements are shown that establish the optimum parameters for minimizing mixing energy requirements, while maintaining adequate solids blending for biological activity. The comparative relationship between laboratory-scale mixing energy estimates and those required for scale-up systems is also established.

Index Entries: Horsepower; mixing; high solids; anaerobic digestion.

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INTRODUCTION

It is generally recognized that the rate of biological fermentation can be enhanced through adequate mixing of the fermenter contents. Mixing allows for intimate contact of the microbial catalyst with the substrate and fermentation intermediates. In the case of anaerobic fermentations, mixing also allows for the product gas (biogas) to be released from the fermentation sludge. Without proper mixing, fermentation rates are slowed, and the extent of conversion may be incomplete. The lack of adequate mixing may also result in the formation of foam or a scum layer in anaerobic digesters, which may seriously jeopardize the safe operation of the system.

For conventional low-solids, continuously stirred-tank reactor (CSTR) anaerobic systems, such as those used in the treatment of municipal sewage, mixing of the fermentation sludge is most often accomplished by conventional impeller mixers. On average, impeller agitation systems represent 3–10% of the equipment costs. The conversion of alternative organic wastes, including municipal and industrial solid wastes, represents an opportunity to reduce the physical size of the anaerobic digester system by reducing the water content of the feed (*1*). Because digestion costs represent from 25–49% of the system capital costs (*2*), smaller digester systems may serve to reduce both capital costs and operating costs (e.g., heating and mixing) for the process. However, because high-solids slurries are very viscous and often resemble solid materials more closely than typical fluids, conventional mixers cannot provide homogeneity in the reactor, and fermentation rates slow down because of inadequate dispersal of microbial catalysts, nutrients, and substrates.

Scant information is available regarding the minimum mixing energy requirements for anaerobic digestion of municipal, industrial, and agricultural solid wastes. However, in one study that utilized a low-solids CSTR system and gas recirculation mixing, energy costs for digester heating and mixing were evaluated in terms of the energy content of the biogas product (Fig. 1). These data indicate that the energy required for digester heating at mesophilic temperatures may be appreciable (i.e., $>$40% of the overall energy content of the biogas product) and that ing required an additional 14.5% of this total (*3*). Thus, for this example, slightly over 39% of the biogas energy product is available for productive use (i.e., excess).

Previous studies on mixing horsepower requirements for anaerobic fermentation have focused on specific mixing systems with an emphasis on reducing the drive motor size required. In general, little attention has been paid to solids settling rates or mixing efficiencies. Instead, the quality of mixing has been determined by gross parameters, such as gas production rates and scum layer formation. Data developed by Smith for a gas recirculation mixing system (3) and James et al. for a hybrid gas recircula-

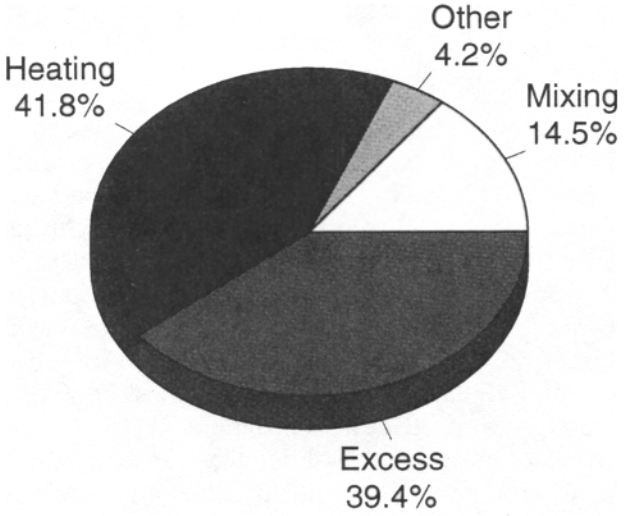

Fig. 1. Energy use as a function of total biogas energy product from low-solids anaerobic digestion operated at 35°C and fed a 4% total solids feed (*3*).

tion/impeller mixer (*4*) were 1.5 and 1.2 hp/1000 ft^3, respectively. Furthermore, James et al. conceded that additional horsepower input would benefit the fermentation and advocated the use of 4.2 hp/1000 ft^3. The RefCoM project (Refuse Conversion to Methane, Pompano Beach, FL) used a conventional CSTR design with impeller mixer and demonstrated horsepower requirements of 2.2–3.2 hp/1000 ft^3 over a 2.5–8% sludge total solids range (*2*).

Although several agitation designs for conducting high-solids anaerobic digestion have been proposed, including gas mixing (VALORGA (*5*) and externally mixed systems (DRANCO) (*6*), information is lacking on the horsepower requirements for mixing high-solids digester sludge. The NREL design previously described uses a horizontal mixer similar to that used in the plastics industry (*7*). Laboratory studies identified the most effective agitator to be a simple tine design with opposing row orientation. Furthermore, fermentation studies showed that only modest levels of mixing (1 rpm) with this agitator were necessary to maintain optimum biological conversion rates (*8*). However, concerns about the expected costs for mixing high-solids materials at an industrial scale warrant an evaluation of the horsepower requirements of proposed designs. This study attempts to identify the horsepower requirements for mixing high-solids materials using a horizontal tine agitator at the speeds previously identified for optimum anaerobic fermentation. Additionally, the influences of sludge solids concentration and reactor fill level on mixing horsepower requirements are investigated.

MATERIALS AND METHODS

High-Solids Digester System

The 20-L laboratory-scale, high-solids digester used in this study was previously described in detail (7). The digester consists of a cylindrical glass vessel positioned with a horizontal axis and capped at each end. The agitator shaft runs horizontally along the axis of the cylinder, and mixing is achieved with a rod-type agitator (tines) attached to the shaft at 90° angles and in opposing orientation. Shaft rotation is powered by a low-speed, high-torque, hydraulic motor. The glass vessel was modified with several ports, including two 3/4-in. ports for liquid introduction and gas removal and a 2-in. ball valve (Harrington Plastics, Denver, CO) used for dry feed introduction and effluent removal.

The intermediate-scale, high-solids digester is a 50-fold volumetric scale-up of the laboratory system and includes a similar agitator, a shaft seal packing gland, and a hydraulic motor system.

Hydraulic Drive System

Initially, a five-piston hydraulic motor (Model HMP-010, Staffa Inc., England) was used for agitation of both laboratory- and intermediate-scale high-solids digester systems. Although this hydraulic motor configuration worked well in all fermentation studies, a roller stator type of hydraulic motor was used in horsepower measurements because the roller stator motor excels in low rpm applications. The laboratory- and intermediate-scale high-solids digesters were equipped with a HB12 roller stator motor (12-in^3 displacement) and a DR46 roller stator motor (46-in^3 displacement) (White Hydraulics Inc., Lexington, KY), respectively.

Horsepower Measurement

Hydraulic motor horsepower was calculated as follows:

$$\text{Motor horsepower} = \text{rpm} \times (\text{torque} / 63025) \tag{1}$$

where rpm is the shaft speed of the motor, and torque is described by the following equation:

$$\text{Motor torque} = \text{hydraulic pressure (psig)} \times (\text{motor displacement} / 2\,\pi) \tag{2}$$

where psig is given in pounds for hydraulic flow, and motor displacement is described in cubic inches. For the operation of a hydraulic motor system at 1 rpm, Eqs. (1) and (2) can be combined and simplified to the commonly used formula described below:

$$\text{Motor horsepower} = (\text{psig} \times \text{motor displacement} / 395{,}998) \tag{3}$$

If the rpm and motor displacement are held constant, motor horsepower is a function of hydraulic pressure to the motor.

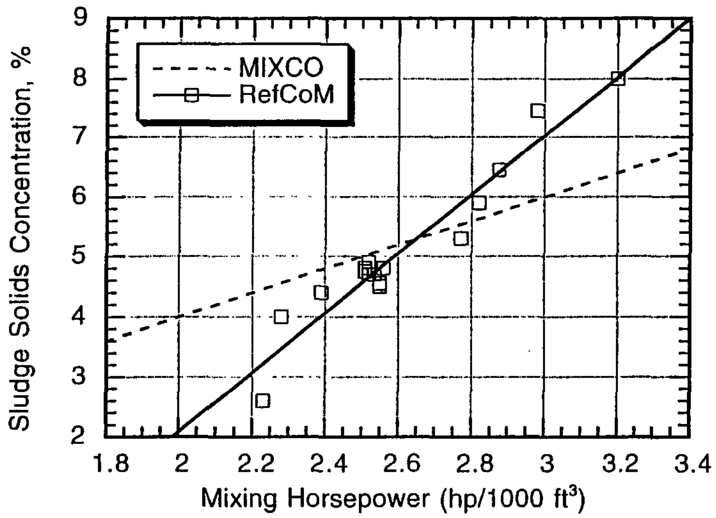

Fig. 2. Effects of digester sludge solids content on the minimum mixing horsepower requirements for low-solids digesters. Both data sets were fit with a linear function used to predict horsepower requirements when mixing at higher sludge solids levels.

RESULTS

Little information is available concerning the horsepower required to mix high-solids anaerobic fermentations, so correlations to data obtained from conventional low-solids systems fed an MSW feedstock were attempted. Mixing requirement data for low-solids impeller CSTR systems were developed by Mixing Equipment Company (Mixco). Mixing data were also obtained from the RefCoM system operation. These data are shown in Fig. 2. The Mixco data were obtained for an anaerobic sludge/processed paper mixture. The high positive slope for the Mixco results describes a higher horsepower requirement relative to increasing sludge solids compared to that determined for actual RefCoM data.

A 20-L laboratory-scale, high-solids anaerobic digester at NREL was used to evaluate the minimum required horsepower for mixing high-solids anaerobic sludge. The data shown in Fig. 3 indicate that a minimum of 100 psi were required to maintain motor rotation and overcome the frictional losses of the reactor shaft seal. Increasing the solids concentration of the sludge within the 15–25% sludge solids range did not significantly alter the required hydraulic pressure for mixing. However, at sludge solids levels of 30 and 35%, dramatic increases in hydraulic pressure were required to maintain mixing in the digester. Digester fill level also demonstrated an effect on required horsepower for the 30 and 35% sludge solids levels with different trends for 30 vs 35% solids sludge.

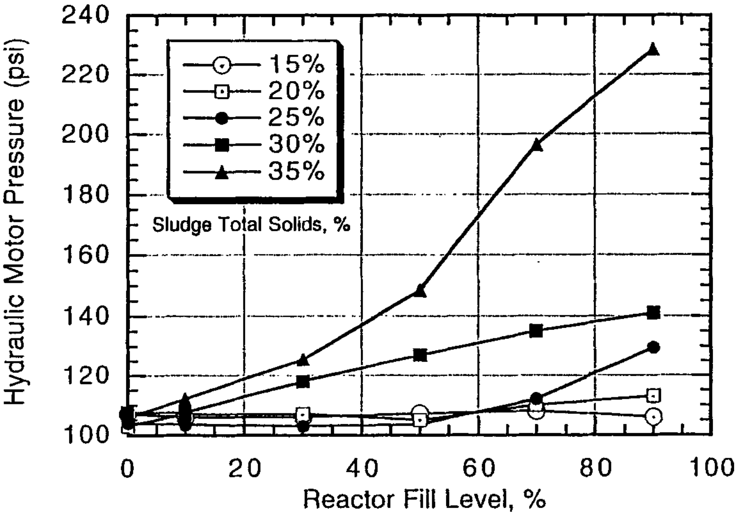

Fig. 3. Effects of increasing sludge total solids and digester fill level on mixing horsepower (expressed as hydraulic motor pressure). The study was conducted with the HB12 roller stator motor at 1 rpm.

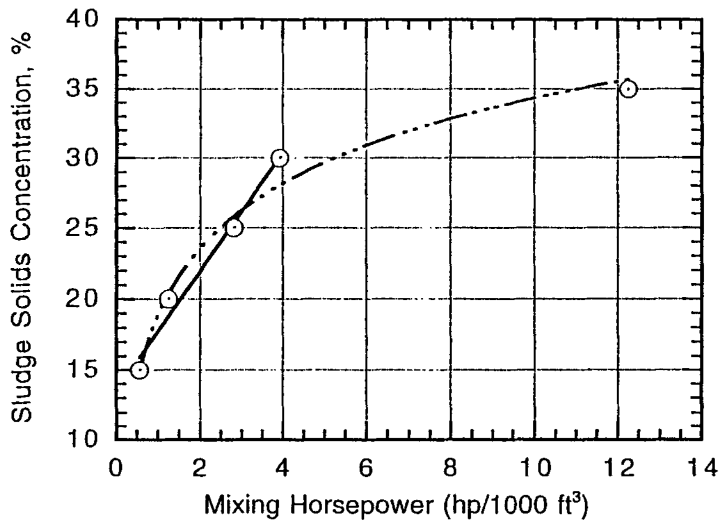

Fig. 4. Effects of increasing sludge total solids on required mixing horsepower for the 90% digester fill level. The first four data points were fit to a linear equation (solid line) that was used to predict required mixing horsepower in the intermediate-scale digester system. An exponential equation was used (dashed line) to include the 35% sludge total solids data.

The data for 90% fill volumes were used to predict the effects of sludge solids on mixing horsepower as given in units of hp/1000 ft^3. These data are shown in Fig. 4 and indicate that two relationships may be inferred. Data for the first four solids levels (i.e., 15–30%) conform to a linear regression (R = 0.989). However, all five data points were best described using an exponential curve (Fig. 4; dashed line).

Table 1
Analysis of Mixing Horsepower Requirements
for the NREL High-Solids, Intermediate-Scale Digester System

Sludge solids, %	Sludge volume, L	Motor pressure, psi	Motor rpm	Mixing horsepower, hp/1000 ft³			
				Mixco	RefCoM	NREL	Actual
19.0	400	175	1	9.5	5.43	1.32	1.42
19.0	500	225	1	9.5	5.43	1.32	1.48
21.0	625	300	1	10.5	5.84	1.78	1.57
26.5	300	275	1	13.3	6.95	3.07	3.02
30.0	312	355	1	15.0	7.65	3.88	3.74

Scale-up work has proceeded on the NREL high-solids digester design, and periodic measurements of horsepower were determined during an 8-mo start-up period. Data in Table 1 compare actual mixing horsepower requirements for the intermediate-scale, high-solids digester system with those predicted by extrapolating the low-solids data for Mixco and RefCoM. Additionally, the linear relationship of higher sludge total solids on minimum mixing horsepower as determined using the laboratory-scale NREL high-solids digester (Fig. 4, solid line) was also used to predict mixing horsepower for the intermediate-scale digester system. In general, the mixing horsepower requirements for the intermediate-scale, high-solids digester are best approximated by the data developed from the laboratory-scale system. The actual horsepower required for intermediate-scale, high-solids mixing was substantially less than that predicted by extrapolating low-solids data from either Mixco or RefCoM.

DISCUSSION

Economic evaluations of the application of anaerobic digestion to treatment of municipal, industrial, or agricultural solid wastes indicate that a major portion of the capital costs are related to the digestion system (25–49%). Additionally, when considering the total energy produced in the form of biogas from such systems, substantial amounts are required for heating and mixing the digester. Process economics may be improved, however, by reducing the physical size of the digester vessel by operation at lower sludge water content (low solids = 2–8% vs high solids = 20–35%). Additionally, high-solids digester systems may be organically loaded at much higher rates per unit volume (i.e., compared to those of low-solids systems) as a result of increased microbial and enzymatic levels (*9*).

Although a variety of cost savings may be incurred by high-solids operation, careful consideration of mixing requirements is a priority. Data for mixing high-solids sludge in small, laboratory-scale digesters were compared to actual mixing requirements for a sizeable intermediate-scale system. The data correctly predicted the required mixing horsepower for the larger system. Additionally, using conventional low-solids mixing data and extrapolating to high-solids conditions proved to overestimate substantially the required horsepower for mixing.

In summary, maintaining digester sludge solids levels at 30% or below results in similar horsepower requirements per digester volume (ft^3) as those found for low-solids digester systems handling from 2 to 8% sludge solids. This may be explained by the requirement of low-solids mixers to reduce solids settling and inhibit scum formation to provide optimum fermentation and safety. Alternatively, mixing in high-solids systems is required to provide gentle contacting of microorganisms, substrates, and nutrients, while releasing intrained pockets of biogas.

ACKNOWLEDGMENT

This work was funded by the Municipal Solid Waste Management Program of the US Department of Energy.

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