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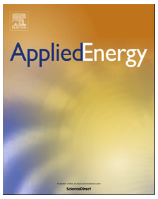

Affordable solar-assisted biogas digesters for cold climates: Experiment, model, verification and analysis

Vergil C. Weatherford, Zhiqiang (John) Zhai *

Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, Boulder, CO 80309-0428, USA

HIGHLIGHTS

- Evaluate the physical performance of affordable biogas digesters for cold climates.
- Improve and validate a 1-D thermal computer simulation model.
- Conduct parametric analysis of the model for key design parameters.

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ABSTRACT

Energy sources are scarce in the chilly, high mountains of the developing world. Solar-assisted biogas digesters have recently been adapted to this climate providing an alternative cooking fuel for some rural families, but little is known about the thermal performance of these digesters. Internal slurry temperature is one of the important design factors in bio-digesters. This study conducted a series of field experiments on an experimental bio-digester in Cusco, Peru to investigate the thermal performance of these affordable bio-digesters. The study further improved and validated a one-dimensional thermal computer simulation model using the experimental results. A set of design recommendations for small-scale, cold-climate digesters is presented based on parametric analysis of the validated model for several key design parameters.

1. Introduction

Anaerobic digestion (AD) technology is a direct way to increase the energy leverage of small farms. However, these benefits can only be realized with a small investment by farmers living in tropical climates. Those who live in colder climates and higher altitudes cannot take advantage of the same type of digesters, as the slurry must be above a certain minimum temperature in order to be effective. Thus, the design must be adapted to colder climates.

Tubular polyethylene bio-digesters emerged in the early 1980s. They were introduced in the developing world as a potential solution to the organic waste and cooking fuel problems faced in rural communities. They are easily constructed out of basic and affordable materials, and only require the addition of water and manure to operate. The first low cost tubular digester was the “red mud PVC” digester, so called because its sheath is made from a polyvinylchloride compound that exists as a reddish slurry byproduct of the aluminum industry [1]. The technology has been improved upon and adapted to many different geographical regions based on available resources and variation in agricultural and cultural practices. Preston improved and simplified the design in Ethiopia (Preston Unpublished), and Botero adapted the design to the materials and construction techniques of Columbia [2]. Later, An et al. improved the design in Vietnam by sourcing ultra low-cost polyethylene-bag material, reducing the material costs even further [3]. Tubular polyethylene bio-digesters have been promoted in a number of other countries including Tanzania, Vietnam, Cambodia, China, Costa Rica, Ecuador, Argentina, Chile, and Mexico [4–6].

Improvements to the initial design have largely been usability improvements, with the basic design staying intact. However, these polyethylene tubular digesters were exclusively built for use in tropical climates. Due to the nature of the microbial processes that take place during anaerobic digestion, a certain minimum temperature is required for reasonable digestion efficiency as detailed by the following literatures. Herrero, in 2003, first adapted Botero’s design to cold climates in the Bolivian *altiplano* by adding a simple shed-roof adobe green-house structure over the digester [7]. Poggio, in Peru, proposed adding a solar water heating system to

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* Corresponding author.
E-mail address: john.zhai@colorado.edu (Z. (John) Zhai).

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the Herrero's design, by storing water in a 10 cm PVC tube running the length of the digester under a modified version of the greenhouse [8]. These studies indicated reasonable temperature range for operating these small scale digesters in cold climates with adequate efficiency.

There have been a number of thermal studies of biogas digesters, including solar heating systems. Recently, in Greece, Axaopoulos et al. simulated the thermal performance (in TRNSYS) and validated with experimental results of an in-ground, plug-flow bio-digester with a single-slope roof consisting of solar hot water panels. They found that slurry temperature was influenced greatly by feeding rate and feed-stock temperature, while the temperature of the air in the gas holder was influenced largely by the ambient temperature. Their simulation agreed with experimental results well [9]. A similar model was developed for a different geometrical configuration in 2004 by El-Mashad et al. using Matlab and Simulink software. Thermal heat recovery from the effluent and waste-heat utilization from the pumping equipment and a structurally-integrated solar hot water array were considered, and found to improve the digester performance by about 4 to 6 °C on average [10]. In 2005, Gebremedhin et al. developed a 1-D thermal model for determining the heating requirements for plug-flow digesters built below grade, partially below grade, and entirely above grade. Validation of the model was carried out using data from two dairy-manure digesters. Agreement was fair, with error less than 20% for all months of the year [11]. Wu and Bibeu developed a 3-D model also describing a large, plug-flow digester, particularly for use in cold climates. The model developed is flexible, with multiple geometries considered. Using the same data as Gebremedhin, the authors found better agreement with the experimental data via the 3-D model. They also conducted a comparison of various geometries for digesters, and found that, as predicted, the cylindrical digester design had lower heat loss than did shapes that were rectangular, rectangular with arched top, or cylindrical with conical bottom [12].

This research seeks to add to the limited body of knowledge about the thermal performance of small-scale, solar-assisted polyethylene digesters, of the kind being built largely in Peru and Bolivia. A series of field experiment were performed on an experimental bio-digester in Cusco, Peru to investigate the thermal performance of these affordable bio-digesters. The study then improved and validated a one-dimensional computer thermal model using the experimental results. Due to many uncertainties in the properties of actual solar-assisted polyethylene digesters that are hand-made with local and cheap materials, the main focus of the study has been put on developing a reliable model with less inputs but providing reasonable results that can help guide the design and construction of bio-digesters for cold-climates. Upon parametric analyses of the calibrated model for several key design parameters, the study presents a set of design recommendations for small-scale, cold-climate digesters.

2. Field experiment

During February and March of 2010, a 7-week field campaign was conducted in the highlands of Peru and Bolivia to collect thermal data on digesters both in the field and in a laboratory in Cusco, Peru. Most of the research took place at the K'ayra satellite agronomy and animal husbandry campus of the Universidad Nacional San Antonio Abad del Cusco (UNSAAC). The research on small-scale bio-digesters there was carried out in association with GREDCH research group from the Polytechnic University of Catalunia (UPC) in Spain.

The bio-digester research facility at K'ayra has four full-scale test digesters, each with a capacity of 2.5 cubic meters of liquid volume. They are located inside a large walled compound which contains the compost, soils and vermiculture center. The digesters are each constructed of a long, polyethylene tube bag set in a hand-dug trench lined with straw for insulation. A low-walled adobe structure has been built over each digester, and covered with "*agrofilm*", a common material used in constructing greenhouses. The digesters are lined up side by side, for ease of access while loading and mixing slurry in the inlet box. The outlet boxes of each of the digesters are plumbed to a canal which carries the liquid fertilizer effluent to a common holding tank where it is allowed to settle, and is then applied to crops. One of the digesters was constructed with 9 ports in the side for taking samples and temperature measurements (see Fig. 1). There is an in-line gas flow meter for each of the four digesters that measure the rate of gas production of each digester that has been used to measure the influence of different feed-stocks on gas production.

The goal of this field experiment was to capture both the local ambient climatological conditions and, simultaneously, a representative sample of temperatures within the digester to ascertain the thermal performance of the digester over time. Besides providing first-hand data of the thermal performance of the tested bio-digester, the collected data is used to improve and validate a simplified computer model upon which various design parameters can be tested.

In order to capture the temperatures inside the digester, the HOBO pendant temperature loggers (which are buoyant) were tied at specific lengths along three strings, each weighted at the bottom and tied to a central cord. Then, using a technique similar to inserting a three masted ship into a bottle, the strings of sensors were pushed into the digester with a semi-rigid length of PVC tubing. Once inside the digesters, the three strings floated upright in the slurry, collecting temperatures for the bottom, middle and surface. Fig. 2 shows the locations of the temperature loggers during the study period and cross-sectional digester dimensions. Fig. 3 shows a side view of the placement of the pendant loggers laterally inside the digester.

A standard Davis anemometer was mounted on a post 1.8 m off the ground near the digester for collecting wind-speed and direction. An EKO MS-602 s-class pyranometer was used to collect total horizontal solar radiation.

2.1. Weighting of internal digester temperatures

Rather than averaging the 9 internal digester temperatures by a simple arithmetic mean, a weighting system was developed in order to give greater influence to the sensors in the middle of the

Fig. 1. Nine sampling ports in the side of one of the test digesters at K'ayra.