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Research paper

Study of solar heated biogas fermentation system with a phase change thermal storage device

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ABSTRACT

A new technique of solar heating biogas fermentation system integrated with a phase change thermal storage device is introduced for improving the low efficiency of the traditional biogas fermentation devices during winter. For a designed solar heated biogas system, its performance of anaerobic fermentation process under the different natural cooling conditions has been assessed by varying the thicknesses of insulation materials. And the optimum relative proportion between the heat supplied by solar and that stored in phase change heat storage device has been also investigated. The preliminary results based on the numerical simulations performed with meteorological data from Anhui Province, China show that the proposed PCM device with 3 m^3 paraffin wax as phase change material (PCM) and 20 m^2 solar collector areas can satisfy the heat required by producing 5 m^3 biogas per day corresponding to a solar fraction (f) of 0.8 in winter. It indicates that the proposed solar heating system could be a promising approach for promoting biogas technology applications in cold rural regions of China.

1. Introduction

Biomass like straw is rich and burnt without any environment protection devices each year in China, which results to air pollution problem like $PM_{2.5}$ becoming seriously in recent years. In view of energy shortages and the abundant resources of straw in China, the biogas industry can be an effective way to meet the demand for clean energy in rural areas [1]. Biogas is a combustible gas which is produced by the anaerobic (i.e. oxygen free) microbial fermentation of organic substances at a certain temperature, humidity and pH value. There are many factors influencing the fermentation process, among which the fermentation temperature is particularly important. Sufficient warmth is the key to the fermentation process, so researchers need to find ways to meet the energy requirements at minimum cost. Another problem encountered in such a bioreactor is how to minimize temperature fluctuations, because they adversely affect the bacterial fermentation process [2]. The temperature fluctuations should not exceed 2–3 °C per hour. If the fermentation temperature fluctuations exceed 5 °C in a short period of time, biogas yield will decrease significantly, so a constant fermentation temperature is required [3–5]. Different kinds of fermentation technologies achieve anaerobic digestion at different temperatures: room temperature (15 °C), medium temperature (30–38 °C) and high temperature (50–55 °C). In rural areas, the medium temperature fermentation process has been shown to be more economical with an optimum temperature of 35 °C [6]. Therefore, it is important, in order to grow and sustain the mesophilic bacteria and obtain optimum biogas production, to heat the bioreactor to a temperature of about 35 °C.

The focus of current research in biogas technology is to use clean energy to improve the fermentation temperature and maintain an efficient biogas production rate in winter. This can reduce conflicts between energy combustion and environmental conservation. And in some regions, where there is plenty of sunshine throughout the year, solar energy is a relatively economical source for heating purposes. In large and medium-sized methane gas projects, the ground source heat pump, boiler and solar greenhouse etc. are used to improve the fermentation temperature. Liu Jianyu et al. (2013) used a groundwater source heat pump to heat the anaerobic fermentation tank in winter, and the total savings in standard coal consumption was only 44% of the demand of standard coal using coal-boilers directly during the experimental cycle [7]. Li Jicheng et al. (2014) proposed to heat the anaerobic fermentation system by using solar energy combined with biomass boiler for ensuring biogas fermentation tank working normally in winter. When solar energy cannot satisfy the heat demand of fermentation tank, the

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biogas boiler will be switched on and complement the deficit of heat demand [8]. When the demand for heating cannot be met through solar energy alone, the biogas boiler will be switched on and send heat to the fermentation tank [8]. Ling Qiu et al. (2008) designed a double-effect solar heated biogas fermentation system consisting of a solar greenhouse and a hot chamber. The solar greenhouse is used to retain heat from the sun and improve the ambient air temperature around the bioreactor, thus reducing heat loss from the fermentation tank and improving the heat utilization efficiency respectively [9].

However, the ground source heat pump, boiler and solar greenhouse etc. are not appropriate in small-sized and household methane gas projects. P. Axaopoulos et al. (2001) designed a solar powered household biogas fermentation system, using flat-plate collectors as an integral part of the roof structure of a swine manure digester [10]. In order to solve the problems of fermentation process in winter in the northeast China, Li B. (2014) studied the gas production rate of fermentation tank with solar heating to improve the temperature, and the experimental investigations were mainly based on the climatic conditions in northeast China [11].

This paper presents a solar heated small-sized biogas fermentation system with a phase change thermal storage device in Anhui Province, located in central China. Different insulation materials were studied under natural cooling to ascertain the optimum, most cost effective material and material thickness, as well as the best relative sizes for the three components of the system, namely: the fermentation tank, the solar heat collectors and the phase change heat storage system. In this study, the appropriate insulation material, the optimal insulation layer thickness and the most suitable solar fraction value are selected. The solar heated phase change thermal storage device can ensure a continuous and efficient fermentation process, which can effectively cope with changes in solar energy resources resulting from diurnal changes, cloud cover, days of inconstant sunshine and seasonal fluctuations.

2. System description

The system mainly consists of three subsystems—heating system, heat storage system and fermentation system, as shown in Fig. 1. The parabolic trough condenser is the main component of heating system and it translates the solar energy into heat. The heat storage device accumulates the surplus heat and supplies heat when there is not sufficient heat-collecting capacity. Furthermore, the storage device reduces the influence of the relatively unstable solar energy heat source and increases the stability of the system. The collected heat is transferred to the heat storage device when the fermentation temperature is higher than 35 °C. When the fermentation temperature is lower than 35 °C, it is used for heating the straw fermentation tank. In summer, the fermentation temperature can reach temperatures above 35 °C, so the biogas production rate is guaranteed and no additional heating is required. The oversupply of solar heat is then transferred to the phase change heat storage device. This process is the heat storage process, as shown in ① loop. On the one hand, the heat stored on sunny, warm days, will be taken out to replenish the heat loss of the fermentation tank when the heat-collecting capacity cannot meet the heat load in winter, as shown in ② loop. On the other hand, when the heat-collecting capacity can meet the heat load, the heat-collecting capacity is supplied directly to the fermentation tank, as shown in ③ loop.

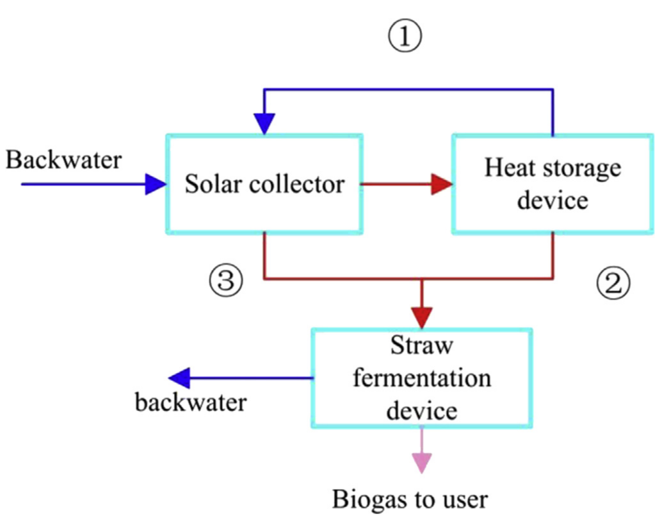

Fig. 1. Schematic of solar heated biogas system with PCM storage tank.

3. Thermal analysis

3.1. Meteorological data and basic value of the system parameters

In this study, the system consisted of three main parts shown in Fig. 1. And a fermentation tank was designed to produce 5 m^3 biogas a day. It was a metallic cylindrical tank with 1.1 m inner diameter and 1.98 m height. In order to keep the efficient fermentation temperature in winter, the fermentation tank needs to be not only insulted by using the suitable thickness insulation material but also heated by the thermal storage device. This device is designed to be filled paraffin wax which is used to keep the thermal energy collected by solar collectors in summer and autumn, since the inside temperature of fermentation tank can work normally due to the high ambient air temperature. When air temperature is below 5 °C of the minimum fermentation temperature and solar collectors cannot supply the enough heat in winter, some additional heat provided by the paraffin wax thermal storage device will complement the heat deficit required by the fermentation system.

The system thermal analysis was generally conducted under the local meteorological conditions in Anhui Province, China, where the demonstration system will be located. The typical data of solar radiation as well as ambient air temperature are listed in Table 1. And the average temperature and the total solar radiation in the local winter are around 5 °C and 627 MJ/m^2 respectively.

3.2. Heat demand and dissipation of the fermentation tank in winter

The heat requirement of the fermentation system is shown in Fig. 2. Here we do not consider that the heat loss due to biogas removal from the bioreactor and the heat generated by the fermentation process. They are negligible and have little influence on the fermentation process [13]. Therefore, the system heat load includes the heat loss (Q_1) dissipating from the insulation enclosure and the heat load (Q_2) of biomass digestive fluid which need to be heated to reach the required operating temperature 35 °C from the ambient air temperature before entering the bioreactor fermentation tank. Then the heat loss (Q_1) and the system total heat demand (Q_2) can be described as:

$$Q_1 = Q_{1a} + Q_{1b} \tag{1}$$

$$Q_{Demand} = Q_1 + Q_2 \tag{2}$$