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Research Paper

Performance of a novel household solar heating thermostatic biogas system

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HIGHLIGHTS

- A novel over-ground household solar heating thermostatic biogas system was developed.
- Full-scale field experiments on biogas production characteristics were conducted.
- The biogas produced can satisfy the cooking fuel demands of farmers even in winter in the cold regions.
- The dynamic payback period of the system with 5.66 years was obtained.

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ABSTRACT

Household biogas plays a critical role in energy supplying and environmental protection in Chinese rural areas. A novel over-ground household solar heating thermostatic biogas system was developed in this study to improve the biogas production rates in winter in cold regions of China. Full-scale field experiments on the biogas production characteristics of the system in seven batches process for more than a year and a semi-continuous process experiment for nearly four months during winter were conducted in cold regions of China, together with the amount of daily heat consumed by the digester in the semi-continuous process. The economic feasibility of the system was also evaluated. The average biogas production rates of 0.63, 0.68, 0.44, 0.64, 0.93, 1.09 and 1.08 $m^3/(m^3$ slurry·d) at T_{80} were determined in seven batches. In the semi-continuous process experiment, four daily biogas production peaks of 1.39, 1.60, 2.39, and 2.15 m^3 emerged on days 35, 56, 74 and 112 respectively. The total biogas yield during the test was 110.71 m^3, with a methane content of 54.74%. The biogas produced in the semi-continuous process satisfied the cooking fuel demands of three to five farmers. The biogas production rate increased rapidly when the amount of time consumed during slurry temperature after reloading was small. The heat consumed by the digester was 15 MJ/d–30 MJ/d during the worst time of the year. The NPV and DDP of the system were 7708 yuan and 5.66 years respectively. Suggestions based on the experimental results were proposed for the efficient use of biomass resources in rural areas and for the improvement of biogas production reliability. The proposed novel household biogas system can play a significant role in using biomass resources to satisfy farmers' cooking fuel demands in cold rural regions.

1. Introduction

Household biogas is a promising technology to satisfy the cooking fuel demands of farmers and protect environment in rural regions of China. This technology has several benefits, such as workload reduction, income generation, health improvement, job production, chemical fertilizers reduction, waste treatment and greenhouse gas mitigation [1–3]. Biogas production by digesters is considerably affected by fermentation temperature and temperature fluctuations. Three fermentation processes existed corresponding to different fermentation temperatures, namely, thermophilic fermentation (45–60 °C), mesophilic fermentation (28–38 °C) and normal temperature fermentation (below 28 °C). Generally, mesophilic fermentation and normal temperature fermentation are the most suitable processes for rural household digesters. Biogas production rate increased with the fermentation temperature raised within such temperature scope [4]. Else, the fermentation temperature fluctuations should avoid exceeding 2–3 °C per hour, thus a relatively content fermentation temperature is needed [5,6]. In the cold regions of China, traditional fixed dome digesters are the most common model developed and used. However, their performances were severely restricted by the ambient temperatures for lack of insulation and warming measures,

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so they are less efficient during winter than in warmer summer months [7–9]. This condition means that biogas can only partly, even rarely satisfy cooking fuel demands of farmers [9,10]. Meanwhile, building traditional household digesters underground is preferred, and the sizes of these digesters always vary from 6 m^3 to 10 m^3, owing to the low fermentation temperature [6], which leads to enormous difficulties in construction, discharging slurry and maintenance, at the same time diminishing utility enthusiasm of farmers. Therefore, developing a highly efficient household biogas system is urgent for the promotion of biogas technology in cold rural regions of China.

Energy conservation and emission reduction technology which involves the use of clean energy to improve the fermentation temperature and maintain the efficiency of biogas production during winter is widely approbatory [5]. In large and medium-scale biogas systems, the ground source heat pump [11], solar energy integrated with the ground source heat pump [12], methane liquid heat recovery heat pump [13], solar and power waste energy [14] and air-source heat pump [15] serve as the heating source to warm the digester. However, these methods are uneconomical for small-scale household digesters.

Plenty of studies explored the use of solar energy as primary or single heating source to improve the biogas production of household digesters. In early years, conventional biogas units integrated with passive solar technologies appeared in India, including collection-cum-storage water heater [16], blackening and double glazed [17,18] and greenhouse [19,20], which could increase the slurry temperature and decrease temperature fluctuations. Usmani et al. [21] proposed a mathematical expression to test the compound system of greenhouse and biogas. Vinoth Kumar and Kasturi Bai [22] evaluated plastic as an alternative material for biogas plant assisted by solar greenhouse on a par with conventional brick material. The plant can be efficiently adopted with minor modifications in hilly regions. Experiments of two-stage solar heating technology were conducted in rural ecological campus biogas system by Qiu et al. [23]. The average fermentation temperature was 10 ± 0.5 °C, and 6 ± 1.0 °C higher than that without heating. Wang [24] analyzed the thermal effect of a solar two calefacient effects on a biogas system through theoretical calculations. But these technologies had been proved only somewhat efficient, which resulted from the low solar radiation and ambient temperature in winters, especially in cold regions [25,26].

For this, active solar technologies were employed, which featured with equipping solar collectors, heat exchangers, circulation pumps, and temperature controllers. Alkhamis et al. [27] combined a solar collector with a water-jacket heat exchanger around the bioreactor, and an inexpensive PID was adopted to maintain a constant temperature. Axaopoulos et al. [28] developed a mathematical model for simulating an innovative design of a solar-heated anaerobic digester, whose fix cover was made of flat-plate solar collectors. Two types of systems with a 10 m^3 reactor and a solar heating system mounted on the reactor were designed by El-Mashad et al. [29]. An auxiliary heater was employed in cold months by operating with the produced biogas. Kocar and Eryasar [30] conducted an experiment on a 280 L cylindrical reactor heated by a flat plate solar collector through a water jacket surrounding the reactors. Optimization of solar energy systems for 5 m^3 anaerobic reactor heating was then performed. A solar heated reactor in reference [31] was a metallic cylindrical tank with a peripheral twin-wall enclosure. The authors developed a mathematical model for the prediction of the temperature distribution under steady state conditions. Abid and Karimov [32] proposed a biogas digester consisting of a methane tank with a built-in solar reverse absorber heater to utilize solar energy for heating slurry. Weatherford et al. [33] explored the thermal performance of solar-assisted polyethylene tubular digesters for cold climates. Meanwhile, Chinese scholars designed different kinds of solar assisted biogas systems for cold regions of China. Yu et al. [34] determined the preferences of an auto solar heating system for constant temperature in biogas digester in theory. A laboratory test on the biogas production of a solar energy constant temperature methane reactor was performed by Li et al. [35]. Su et al. [36] utilized a U-tube solar collector with a 2 m^2 collector area to meet the heat demand of a 6 m^3 digester in October; the collector needed to operate 8 hours a day. The use of parabolic trough solar concentrators (PTC) as heat source of biogas engineering was researched in [37]. Great energy and environmental benefits can be achieved by use of PTC. Li et al. [38] divided the traditional biogas digester into three parts. Only the anaerobic digestion sections were heated to reduce the heated volume and the heat dissipating surface. A new solar heating biogas fermentation system integrated with a phase change thermal storage device for cold rural areas in China was introduced by Tian et al. [5]. The device stores heat on warm sunny days, and replenishes the heat loss in the fermentation tank during winter.

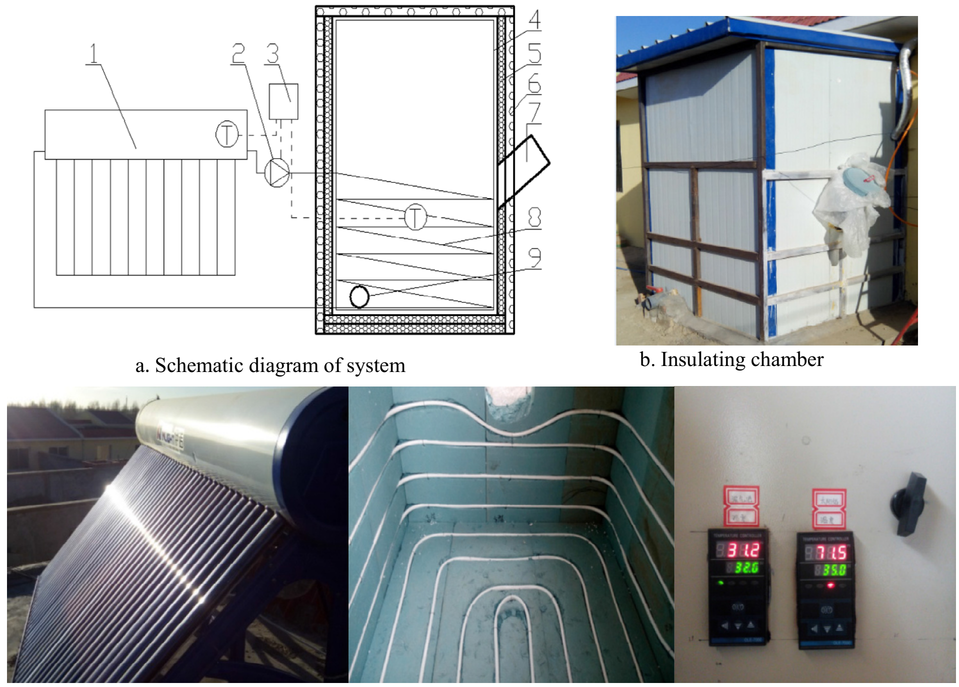
To the best of our knowledge, although a number of solar-heated household digester patterns have been proposed, most of the studies involved were conducted at laboratory scale and in theory, only a few studies have been conducted under practical conditions, and their technical and economic feasibility for cold regions of China remains to be proven. Therefore, a novel over-ground household solar heating thermostatic biogas system was developed. This paper aims to verify the technical feasibility of a new system, which conducts full-scale field experiments on biogas production characteristic and the amount of daily heat consumed by the digester in the coldest time in cold rural regions in China. These experiments included batch process experiments in Gaolan County (latitude 36°24′N, longitude 103°53′E) for more than a year and a semi-continuous process experiment in Minqin County (latitude 38°34′N, longitude 103°3′E) for nearly four months during winter. Besides, the economic analysis is also performed.

2. System descriptions

Fig. 1 shows the structure of the novel over-ground solar heating thermostatic biogas system, which is composed of an all-glass evacuated-tube solar water heater, an insulating camber with a fixed red mud plastic digester, a self developed temperature controller connected to two temperature sensors located in the digester and storage tank of the solar water heater, a circulating pump, a heat coil, and other accessories.

The insulating camber was installed on the ground, and constructed into a cuboid by a color plate with a built-in expanded polystyrene board (EPS) (10 cm depth). An extruded polystyrene board (XPS) with 6 cm depth was placed on the inside surface of the color plate. Two layers of XPS with 6 cm depth XPS were laid at the bottom of the insulating camber. An aluminum plastic tube was utilized as the heat coil embedded in XPS located at the lower part of the insulating camber and connected to the solar water heater. A frame was welded by a square steel to fix the insulating camber. A manhole was set at one side of the façade to enable the workers to fix and maintain the red mud plastic digester later. The high thermal resistance of EPS and XPS would reduce heat loss in the digester.

The red mud plastic fermentation digester utilized in the batch processes was 3.1 m^3 (1.3 m × 1.5 m × 1.6 m). Another red mud plastic bag with the same size was placed above the digester to store the produced biogas. An advanced 6.4 m^3 (1.6 m × 1.6 m × 2.5 m) red mud digester integrating the fermentation and storage together was used in the semi-continuous process. When applied in actual engineering, the lower digester is filled with slurry, and the upper one is used to store biogas.



a. Schematic diagram of system b. Insulating chamber

c. Solar water heater d. Heat coil e. Temperature controller

1. Solar water heater 2.Circulating pump 3. Temperature controller 4. Red mud plastic digester 5. XPS 6. EPS 7. Inlet 8. Heat coil 9. Outlet

Fig. 1. Over-ground thermostatic household biogas system.

The inlet of the digester was polyvinyl chloride (PVC) pipe with 30 cm diameter and 1.2 m length. The pipe passed through the color plate and XPS and then plugged into a customized sleeve of the red mud plastic digester. The inclination angle between the inlet axis and level was nearly 45°. The distance between the low edge of the inlet and bottom surface of the digester was approximately 1.2 m, indicating that the maximum volume that can be filled with slurry was approximately 3.0 m^3. Another PVC pipe with 11 cm diameter connected to a ball valve was also plugged into a sleeve at the bottom of the red mud plastic digester; the outlet was then formed. The model of the inlet and outlet facilitated the easy reloading of slurry in the digester.

The thermostatic principle was as follows. The heat energy collected by the solar water heater was stored in water in the storage tank, and the circulating pump was directly controlled by the temperature controller, which can be set at an initial value beforehand. If the fermentation temperature is below this value, the temperature controller will start the circulating pump. Then the hot water will transfer heat to the biogas digester through the heat coil to improve the fermentation temperature to the set. Similarly, the circulating pump will shut down if the fermentation temperature is above the set limit. All of these actions would occur under the condition that the temperature in the storage tank is higher than that in the digester.

Compared with the traditional biogas system, several distinctive features existed in this new system. Firstly, it is convenient to build and maintain the system due to the over-ground model; secondly, the biogas production can be adjusted via changing the fermentation temperature; finally, the system can also supply domestic hot water to farmers in the warmer days.

3. Methods

3.1. Batch and semi-continuous process experiments

Seven batches of fermentation experiments were conducted from October 17, 2013 to November 3, 2014. Table 1 shows the detailed parameters of the batch experiments. The raw materials were all derived from nearby farms. Maize straw, grass, and cabbage leaves were shredded into 3–4 cm pieces before utilization. The amount

Table 1
Parameters of batch process experiments.

Experiment No.	Start date	Finish date	Fermentation temperature/°C	TS of pig manure/%	Volume ratio of raw materials (pig manure:other:water)
1	Oct. 16, 2013	Dec. 10, 2013	28	35.0	1:0:2
2	Dec. 15, 2013	Jan. 22, 2014	26	39.4	1:0:2
3	Jan. 27, 2014	Apr. 25, 2014	26	38.1	1:1(maize straw):2
4	Apr. 28,2014	June 20, 2014	32	36.2	1:1(maize straw):2
5	June 26, 2014	Aug. 6, 2014	37	37.0	1:0:2
6	Aug. 12, 2014	Sep. 5, 2014	37	28.2	1:1(grass):2
7	Sep. 21, 2014	Nov. 3, 2014	32	36.1	3:4(cabbage leaves):4

of inoculum in each batch was 0.5 m^3. The initial batches were obtained from a biogas power project in Huazhang, Lanzhou. The subsequent batches were self-supplied. When feedstock was utilized, the raw material and hot water were mixed before being added to the digester. The total solids (TS) of the pig manure were determined by drying at 105 °C for 24 h in a laboratory at Lanzhou University of Technology. The total volume of slurry in experiments was 2 m^3, which was calculated according to the slurry level when the feedstock was depleted.

The semi-continuous experiment was conducted with the participation of a farmer family from December 1, 2014 to March 26, 2015. Dry sheep manure with TS 74.36% provided by the family was the unique raw material. Only 70 L inoculum from the laboratory of Lanzhou University of Technology was seeded when the first feedstock was used. The fermentation temperature and operations during the experiment are described in detail in Section 4.2.

Daily biogas production was measured with a biogas meter (manufactured by Zhejiang Xinlong Instrument Co., Ltd., with a precision of ±1.5%) connected to a vacuum pump to extract the gas from storage bag at 17:00. Daily biogas production was determined according to the indication difference of the biogas meter. The methane contents were determined with a biogas check (manufactured by Geotech, UK, with a precision of ±2%). Daily methane production was calculated by timing the daily biogas production with the corresponding methane content.

3.2. Measurements of heat consumed by the digester

The amount of heat transported from the solar water heater to the digester was calculated by measuring the inlet and outlet temperatures of the heat coil with platinum resistance temperature sensors (pt100, manufactured by Beijing Sailing Technology Co., Ltd., with a precision of ±0.1 °C) and the flow rate of hot water with an LWGY-15 turbine flow meter (manufactured by Shanghai Huaman Industrial Co., Ltd., with a precision of ±0.45%). The ambient temperature near the digester, the slurry temperature, and the hot water temperature in the storage tank of the solar water heater were also measured with pt100. All these data were automatically scanned at 10 s intervals and recorded by Agilent 349702.

3.3. Economic analysis

The indexes of the net present value (NPV) and the dynamic payback period (DPP) were adopted to evaluate the economic feasibility [39]. NPV is defined as the difference between the present value of annual income and expenses, which is calculated by Eq. (1):

$$\mathrm{NPV} = \sum_{t=0}^{n} (B - C)_t (1 + i_c)^{-t} \tag{1}$$

in which B and C represent the benefits and the costs respectively, thus the $(B - C)t$ is the net cash flow in the year t; i_c is the discount rate, 4.9% is selected according to the newest loan interest rate in China [40]; t is the operation life; n is the system life.

For the novel system, B can be determined as follows:

$$B = B_b + B_h + B_f \tag{2}$$

where B_b is the benefit by using biogas as cooking fuel; B_h is from the thermal energy supplied by the solar water heater; B_f is the cost savings of reduction in the use of chemical fertilizers and benefits result from the increase of crop production by using biogas fertilizer.

The values of B_b and B_h are usually equal to the costs of traditional energy which supplied the same energy with biogas and hot water. Standard coal is adopted here as the contrast energy [41,42]:

$$B_b = \frac{V C_o q_b \eta_b}{q_{sc} \eta_{sc}} B_{sc} \tag{3}$$

$$B_b = \frac{Q}{q_{sc} \eta_{sc}} B_{sc} \tag{4}$$

where V is volume of biogas produced; C_o is the Content of methane; q_b is the lower heating value of methane, 36.0 MJ/m^3; B_{sc} is the price of standard coal; η_b and η_{sc} are the combustion efficiency of biogas and coal stove, 60% and 35% are selected [43]; q_{sc} is the lower heating value of standard coal, 29.3 MJ/kg; Q is thermal energy supplied to the user by solar water heater in the warmer days.

The costs of the system are composed of two parts:

$$C = C_{inv} + C_{o\&m} \tag{5}$$

where C_{inv} represents the initial investment of the whole system and is introduced in Section 4.5; $C_{o\&m}$ is the annual operational and maintenance costs.

DPP is the period after which the capital invested has been recovered by the discounted net cash inflows from the system, and can be calculated by Eq. (4):

$$\mathrm{DPP} = T - 1 + \frac{|\mathrm{NPV}_{T-1}|}{(B - C)_T (1 + i_c)^{-T}} \tag{6}$$

in which T is the number of the year when NPV is >0 for the first time.

4. Results

4.1. Biogas production and methane content in the batch process experiments

The daily biogas production and methane contents in the batch process experiments are shown in Fig. 2. In the first experiment (Fig. 2A), the daily biogas production was 0.77 m^3 on the first day; this value increased rapidly afterward. Two peaks, 1.87 and 1.67 m^3, occurred on days 9 and 23, respectively. Then, production decreased gradually as a result of raw material depletion. Compared with the second (Fig. 2B) and fifth (Fig. 2E) experiments with the same raw material but under different fermentation temperatures, only an evident peak at 2.09 m^3 on day 7 appeared in the second experiment. Two high-yield periods occurred in the fifth experiment. With regard to methane content, the first experiment had a faster growth rate than the second one, and higher content was achieved in the beginning of the fifth experiment than in the others. Considering that less biogas was produced during the later stage of the first experiment, the cumulative productions of biogas and methane before 39 days of fermentation periods were compared. The volumes produced were 45.94, 42.52, and 64.15 m^3 for biogas, and 21.88, 20.47, and 38.80 m^3 for methane. More biogas and methane were produced when the fermentation temperature within mesophilic fermentation was high.

Co-digestion of pig manure and maize straw was conducted in experiments 3 and 4. The third experiment had the longest fermentation time but the lowest biogas output in the early period of the experiment, as shown in Fig. 2C. The result is attributed to the slow degradation rate of straw [44,45]. However, with the high fermentation temperature in the fourth experiment (Fig. 2D), the daily biogas productions surpassed 1.0 m^3 for 32 days before day 42. Moreover, the second high-yield period in experiments 3 and 4 was more considerable than the first, which was different from the other experiments. Nearly 70% methane contents were obtained in the later stage of experiments 3 and 4. The high fermentation temperature was

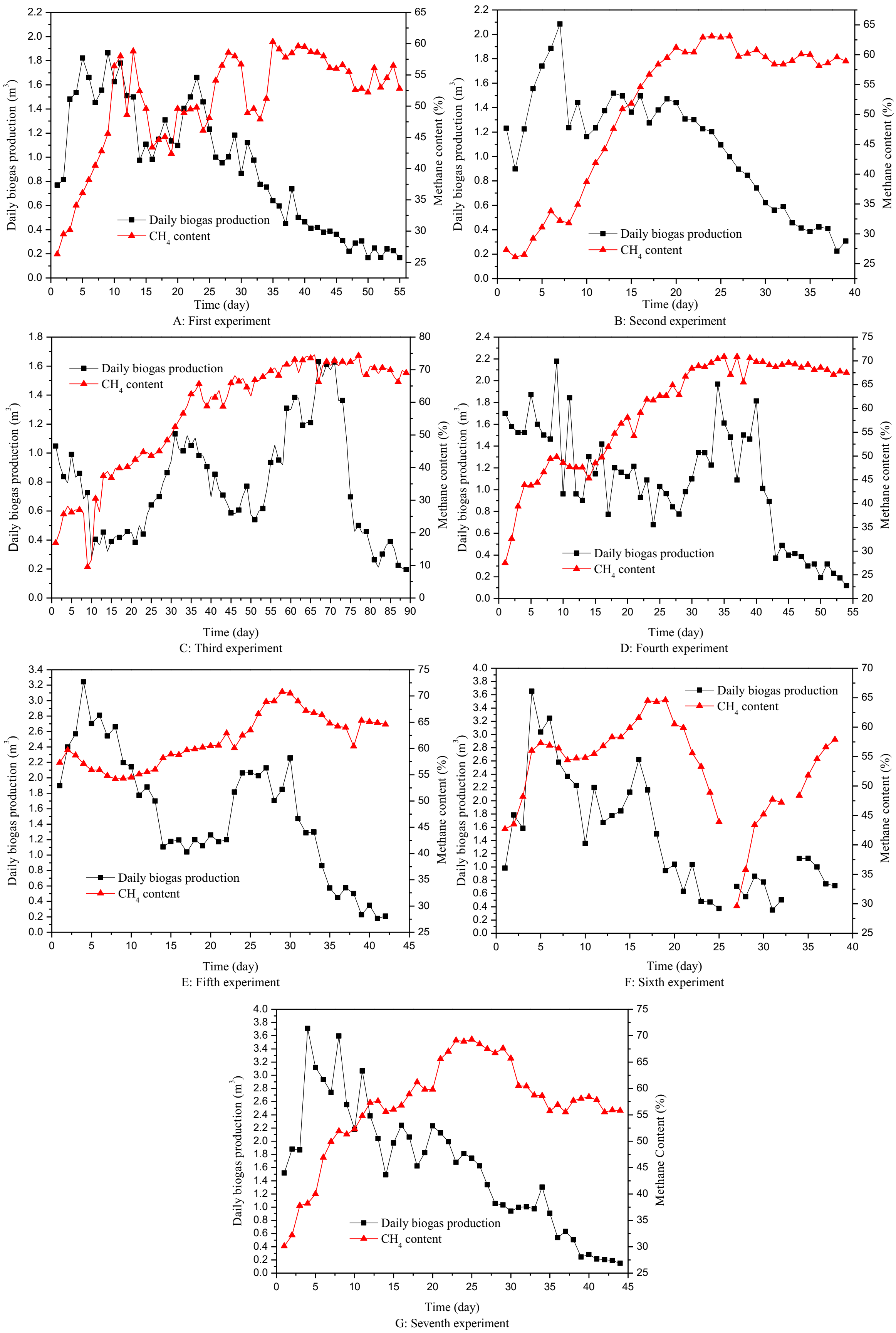


Fig. 2. Daily biogas production and methane content in the batch process experiments.

Table 2
Analysis of the results of the batch process experiments.

Experiment No.	1	2	3	4	5	6*	7
Biogas (m^3)	50.71	42.52	69.38	57.79	64.89	43.72	70.52
Methane (m^3)	24.55	20.47	40.72	32.88	38.28	24.68	38.67
T_{80} (day)	32	25	63	36	28	16	26
Rate ($m^3 \cdot m^{-3}$ slurry$\cdot d^{-1}$)	0.63	0.68	0.44	0.64	0.93	1.09	1.08

* Total biogas and methane production for the first 25 days.

not only conductive for the increase in the degradation rate of maize straw, but also ideal for obtaining methane contents by co-digestion.

Among the seven batches of experiments, the two highest daily biogas yields appeared on day 4 with 3.71 m^3 in the seventh experiment and day 4 with 3.66 m^3 in the sixth experiment. The sixth experiment had the shortest test period but large biogas yields for nearly 20 days. This result may be attributed to the high fermentation temperature and synergistic effect of co-digestion. Then 0.017 m^3 and 0.025 m^3 raw materials with the same volume ratio of initial feed stock were added to the digester on days 26 and 31. The daily biogas production accelerated rapidly, as shown in Fig. 2F. Strictly speaking, the sixth experiment was not a batch process. Experiment 7 also benefitted from the same factors.

The total biogas and methane in the batch process experiments are shown in Table 2. Technical digestion time (T_{80}) is always adopted to investigate substrate biodegradability [46–48]. T_{80} is the time required to produce 80 of the maximal digester gas production. The experiments in this study were terminated when the daily biogas production decreased to approximately 0.2 m^3. The total biogas production obtained was considered the maximal digester biogas production and utilized to calculate T_{80}, and the average biogas production rate per slurry volume during T_{80}, as shown in Table 2. The third experiment had the smallest value for the reasons described above, but good results were obtained from the others, particularly experiment 2, which was performed during the coldest time of the year. The average rate of biogas production during T_{80} with 0.68 $m^3/(m^3$ slurry$\cdot$d) was determined. In summary, the results showed that the developed system has adequate capacity to satisfy the cooking fuel demands of farmers in cold rural regions of China all year if managed properly.

4.2. Operation, biogas production, and methane content in the semi-continuous experiment

Generally, household biogas always operates in a semi-continuous process because of the low amount of biogas produced during the later period of batch process, as shown in Fig. 2. When feeding the raw materials for the first time in the semi-continuous experiment, 0.75 m^3 (calculated according to the volume of the vessel used to carry raw material, the same as below) of dry sheep manure, 70 L of inoculum and moderately hot water were added to the digester. The total volume of the slurry was 1.7 m^3 (also calculated according to the slurry level after feedstock was depleted, the same as below). On day 23, 0.2 m^3 of dry sheep manure was added again to the digester. Then, the slurry level increased by approximately 5 cm. On days 47, 65, and 105, 0.5, 1.1, and 0.8 m^3 of slurry were discharged from the digester. Sheep manure with volumes of 0.4, 0.7, and 0.4 m^3 and some water were added to the digester. The total slurry volumes in the digester were 1.9, 2.1, and 2.2 m^3 after reloading. Likewise, human excreta of the participating family were also added to the digester randomly during the experiment.

The hourly slurry temperature, hot water temperature in the storage tank of the solar water heater, and ambient temperature variations are shown in Fig. 3. The temperature controller and circulating pump began to work because the initial slurry temperature was nearly 18 °C when feedstock was depleted. To avoid reducing the activity of methane bacteria caused by the abrupt temperature increase, the increased temperature was controlled by 2 °C every day. Five days later, the slurry temperature reached the designed value and was the maintained at (27 ± 2) °C. To increase the biogas yield and meet the cooking fuel demands during the spring festival in China, the fermentation temperature was set to 30 °C after the fourth reloading of the slurry. The slurry temperature decreased in different degrees after new raw material was added to the digester but increased again abruptly because of the heat. The time for slurry temperature to return to 27 °C after was approximately 2, 4, 1, and 2.5 days.

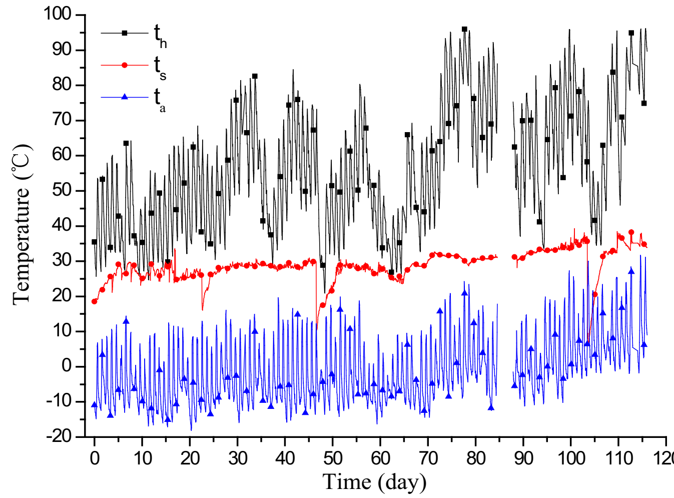


Fig. 3. Temperature variations in the semi-continuous process. t_h, t_s and t_a are the temperatures of hot water, slurry and ambient.

The daily biogas production and methane content in the semi-continuous process experiment are shown in Fig. 4. A small amount of biogas was produced in the initial stage of the experiment possibly because of the shortage in inoculum. The first measurements were obtained on day 4. Daily biogas production did not exceed 0.5 m^3 until day 20, and the corresponding methane content was 49.1%. Later, daily biogas production increased initially, decreased, and then increased again after reloading. Hence, four peaks of daily biogas production, namely, 1.39, 1.60, 2.39, and 2.15 m^3, emerged on days 36, 56, 74, and 112, respectively. The time that the daily biogas production surpassed 1.0 m^3 after three instances of reloading

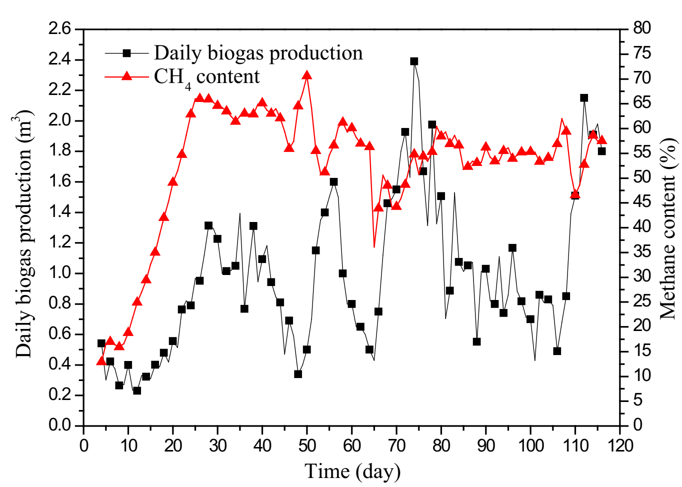


Fig. 4. Daily biogas production and methane content in the semi-continuous experiment.

was approximately 5, 2, and 4 days. Similar to biogas production, the methane content was also limited initially but increased sharply from 16.6% on day 9 to 66.0% on day 25. Fluctuation was observed in the methane content curve near the reloading date because air was brought in by fresh raw material and temperature fluctuations.

The measurements on the semi-continuous process experiment were completed after day 116. Thereafter, the biogas system was utilized and managed by the participating farmer family. The total volumes of biogas and methane generated during the testing periods were 11.07 m^3 and 60.58 m^3 respectively.

4.3. Daily heat consumed by the digester

Solar radiation and ambient temperature in northern hemisphere have their lowest values in winter resulting in the largest heat loss of the digester and least heat energy collected by the solar water heater in the developed system. An all-glass evacuated-tube solar water heater with 40 tubes and a 400 L storage tank were utilized to collect solar energy in the experiment. As shown in Fig. 3, the daily average ambient temperature was within –10 °C to 0 °C during the period. The minimum ambient temperature of –18.2 °C appeared on the morning of December 21, 2014, but slurry temperature was retained at a satisfactory level. Fig. 5 shows the daily amount of heat transported from the solar water heater to the digester. The heat energy consumed by the digester was 15 MJ/d–30 MJ/d most of the time; this value increased for several days after reloading, because the new raw material was needed to be heated to the suitable temperature. The parameters of temperature and flow rate loss from days 85 to 88 were due to the breakdown of Agilent 349702, as shown in Figs. 3 and 5.

4.4. Suggestions

The operating conditions had crucial influence on the biogas production of the system. It is observed in batches of experiments that the high fermentation temperature was not only helpful for increasing biogas and methane yield. Yield would be enhanced if co-digestion is utilized, but conductive for quick degradation of maize straw as well. In semi-continuous process, the rate of biogas production increased rapidly as the time consumed during slurry temperature increased after reloading was reduced. To meet the cooking fuel demands of farmers, several suggestions are proposed to efficiently use biomass resources in rural areas, and improved the reliability of biogas production based on these results.

First, if a shortage in animal manure is encountered, the fermentation temperature could be set to a high value (35 °C–37 °C) on warm days. The mixture of crop straws, which have a slow degradation rate, and animal manure is better for use as raw materials. Operations of lower fermentation temperature (26 °C–30 °C) and using animal manure or substrate which is easy to decompose as raw materials should be implemented in cold seasons.

Second, reloading slurry with large volume should be conducted before winter. When daily biogas production decreases, a new raw material should be mixed with some limpid slurry discharge and hot water from the solar water heater to reuse heat energy from the digester and avoid large temperature decreases after feedstock. Sunny day is still necessary for feedstock in winter.

Third, for insurance purposes, the average daily heat collection of a solar water heater should be set to almost 30 MJ in December and January when a household biogas system is constructed in other cold rural regions (where the daily average ambient temperature is within –10 °C to 0 °C during the coldest month).

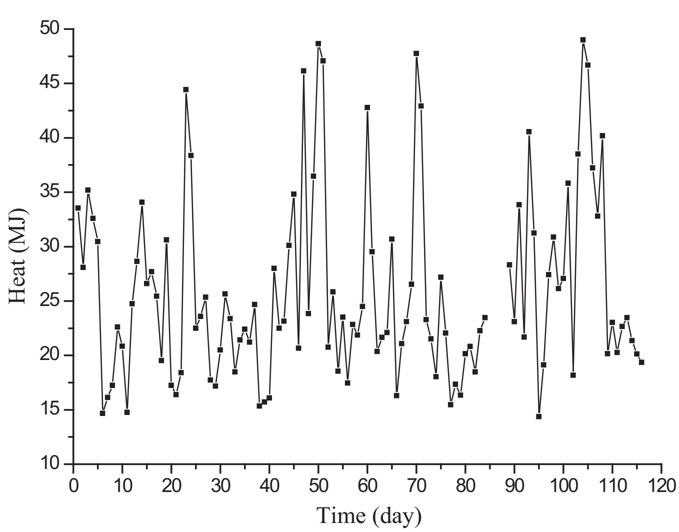


Fig. 5. Daily amount of heat transported from the solar water heat to the digester.

4.5. Economic evaluation

The initial investments, and annual operational and maintenance costs of the system are shown in Table 3. The total investment costs were 6650 yuan, while the conventional biogas digester of 8 m^3 nowadays is nearly 4000 yuan [4], whose annual biogas yield is 400 m^3 and close to the novel system. The higher part is mainly on the solar water heater. $C_{o\&m}$ of 100 yuan is chosen based on the practical experience, which is exclusive of labor costs. Meanwhile, V of 400 m^3 is used in Eq. (5). C_o is assumed as 60%. B_{sc} of 1.5 yuan/kg is determined according to local conditions. As for Q, Wang [49] calculated the thermal energy supplied by solar water heater for rural buildings after a survey. A conservative value of 16.8 MJ/d was obtained, which is equivalent to the energy consumed by heating 80 L water from 10 °C to 60 °C. Take into consideration the fact that during the colder days, the solar water heater would ensure the suitable fermentation temperature first. The number of days that the solar water heater could supply enough domestic hot water was given by 210 days in non-heating seasons, when the solar radiation and ambient temperature were higher than that during the heating seasons. Based on above, the results of B_b and B_h are 758 yuan/a and 516 yuan/a respectively. B_f in this study is assumed as 200 yuan/a. Thus, the annual benefits of 1474 yuan are achieved. Finally, the NPV of the novel system is 7708 yuan when the system life is 15 years, and the DDP 5.66 years as well, which demonstrate well economic feasibility.

5. Conclusions

This study focused on the technical and economic performance of a novel over-ground household solar heating thermostatic

Table 3
The initial investments and annual operational and maintenance costs of the system

C_{inv}								$C_{o\&m}$
Solar water heater	Insulating camber	Red mud plastic digester	Temperature controller	Circulating pump	Heat coil	Accessories	Total	
2000	2400	1000	500	150	100	500	6650	100

biogas system. The biogas productions in seven batches showed that the developed system has adequate capacity to satisfy the cooking fuel demands of farmers in the cold rural regions of China the whole year if managed properly. The average rates of biogas production during T_{80}, namely, 0.63, 0.68, 0.44, 0.64, 0.93, 1.09, and 1.08 m^3/(m^3 slurry·d), were achieved. In the semi-continuous process experiment, four daily biogas production peaks of 1.39, 1.60, 2.39, and 2.15 m^3 emerged on days 35, 56, 74, and 112, respectively. The total biogas yield during the test was 110.71 m^3, with a methane content of 54.74%. The volume of produced biogas can satisfy the cooking fuel demands of three to five farmers. The biogas production rate increased rapidly when a small amount of the time was consumed during slurry temperature increase after reloading. In addition, the amount of heat consumed by the digester to maintain its suitable fermentation temperature was 15 MJ/day–30 MJ/day during the worst time of the year. The NPV of the system is 7708 yuan when the system life is 15 years, and the DDP 5.66 years as well, which demonstrate well economic feasibility. Based on the experimental results, suggestions were provided for the efficient use of biomass resources in rural areas and improvement of biogas production reliability.

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