Design and preliminary experimental research on a new biogas fermentation system by solar heat pipe heating

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Abstract: Biogas fermentation requires appropriate temperature, while the biogas fermentation can be affected by the low ambient temperature in winter. In order to overcome the negative effects of low temperature fermentation, a new type of solar heat pipe biogas fermentation heating system was designed and a preliminary experiment research on this system was conducted using cow manure as the raw material at 6% concentration and total fermentation volume of 175 L. The experimental results showed that when the system was in normal operation, the fermentation temperature rose every day by gradient. This gradient will gradually become smaller with the increase of fermentation liquid temperature, and the temperature can reach 38℃ after stability. Using this solar heat pipe heating system, the fermentation liquid temperature can be increased by 5℃ every sunny day. This solar heat pipe heating system plays a significant role in biogas fermentation. The results of economic analysis show that the system can realize the fermentation at constant temperatures of 25℃ and 35℃ respectively, and it can also save standard coal equivalent of 40 kg and 80 kg in winter and spring, respectively.

Keywords: Biogas fermentation, solar heat pipe, heating system, fermentation temperature, economic analysis
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1 Introduction

As one kind of renewable energy, biomass energy is being paid much attention recent years due to background of the increasingly prominent energy and environment problems. Among the technologies of utilizing biomass, producing biogas energy from biomass is the key of importance. When the biomass is used to produce biogas, suited temperatures are required for the fermentation process[1-5]. However, most biogas digesters are built underground in the rural areas of China, which made the fermentation temperatures vary dramatically with the environment temperatures, especially in the winter time, the fermentation temperature is so low that it causes the digesters to unable to produce biogas. Since the biogas yield is affected by the ambient temperature, the use and promotion of biogas in rural areas are severely constrained. The biogas production technology in the winter is the key technical problems to be solved at this time[6].

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In order to ensure a stable biogas production rate in the construction of biogas projects, improving the fermentation liquid temperature and preparing facilities insulation are important preconditions for biogas fermentation in the seasons with low temperature, which means it is important to take appropriate insulation measures as well as to support the heating system to ensure a constant temperature of biogas fermentation. Many researchers have carried out the work in this area in the recent years. Xiang and Gao[7] conduced a research on the electrothermal film heating system. This system has many advantages, such as temperature uniformity, high energy conversion rate and less influence of the external environment (geography and weather, etc.) and so on. This system is helpful to solve the problems of the digester heating and insulation in the winter. However, the electrical heating system needs to consume a large amount of high-grade energy, increasing the investment of this system. Zhao et al[8] worked on the heating boiler water circulation digester technology, which is based on consumption of large amounts of fossil fuels. Yutaka et al[9] proposed to use hot gas heating system to heat the bioreactor. This heating system consumed biogas. Also, some researchers[10] proposed the use of ground source heat pump for heating. For this system, the heat is transferred from groundwater to the water in coil through the consumption of electricity.

In order to reduce the consumption of fossil energy in the heating system, some researchers[11] applied urban waste heat recovery system to heat fermentation liquid. Parts of the waste heat are recovered and the fossil energy consumption is reduced by using this system. However, the biogas industry is mainly concentrated in the countryside, there is not enough waste heat to be used, which causes the restricted application of the waste heat recovery system in the countryside of China. Some researchers[12-21] proposed the use of solar water heaters to heat fermentation liquid. The system is convenient, easy to operate, and is economically friendly. However, the utilization of solar energy is influenced by the weather for this system. The heat transfer efficiency is relatively low and the pipeline insulation performance is poor resulting in serious heat loss. In this research, a new anaerobic fermentation system by solar heat pipe heating was proposed to help improve the efficiency of the solar energy to be more economically. The heating system is operated by the solar energy and the heat pipes are used as the heat transfer element. The heat is transferred from the heat pipes to the circulating heat exchange system, which is used to heat the fermentation liquid. Using this new anaerobic fermentation system by solar heat pipe heating, the preliminary experimental research was conducted.

2 Design of the system

The basic structure of a new solar heat pipe biogas fermentation heating system is shown in Figure 1. This system mainly consists of fermentation system, heat exchange system and solar heat pipe collecting system. In this system, the heat exchange tubes are located in the biogas digester and the heat pipe collecting system is fixed outside of the biogas digester. The main purpose of heat pipe collectors is to absorb solar energy and as well as to heat circulating water. High temperature circulating water supplies the heat for the fermentation liquid, wherein methanol is selected as the working fluid for the heat pipes.

The design of this system mainly includes three parts: fermentation system, heat exchange system and solar heat pipe collecting system. The detailed description on the design of the three parts will be explained in the following sections.

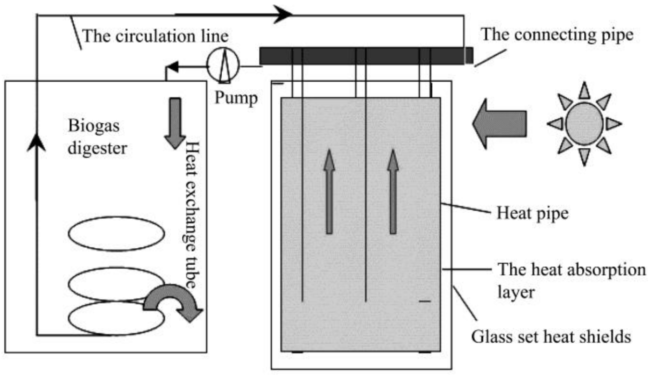

Figure 1 Anaerobic fermentation system with solar energy heat pipe supplying heat

2.1 Biogas fermentation system

2.1.1 Size and materials of system

When this system is operated in the winter time, in order to obtain a better anaerobic fermentation gas yield during the winter seasons, the fermentation liquid should be maintained at a high stable temperature level. The results showed that when the fermentation temperature changes by 5℃, the amplitude of the fluctuation increases dramatically, and it will not only cause the biogas yield to decrease significantly, but it will thus cause the digester to stop producing gas[3]. The temperature control measures are usually taken in the design of fermentation digester to ensure the digester run as much as possible at a constant temperature.

Because of the low temperature in winter, it is necessary to install insulation layer for the fermentation tank to reduce all the heat losses. The insulation layer consists of two parts: the insulating layer and the protective layer. The insulating layer is filled with blowing agent for increasing the thermal resistance and reducing heat losses. The protective layer is mainly composed of an aluminum foil tape and is used to protect the insulating material, fireproof, waterproof and moisture-proof. The protective layer is generally close to the insulation layer when installed.

The volume of this fermentation system will be designed for 200 L. Rubber insulation cotton with the thickness of 10 cm is added to outside the bottom and top of fermentation digester. The gap between the wall and the collector body frame are filled with foam blowing agents of 10 mm to reduce the heat loss. The thermal conductivities of rubber cotton and polyurethane foam are 0.038 w/(m·K) and 0.05 w/(m·K), respectively.

The biogas digester is made with 201 stainless steel materials. The type of the fermentation tank is Continuous Stirred Tank Reactor (CSTR) cylindrical reactor with the diameter of 500 mm, the height of 1000 mm, the thickness of 1.2 mm and the thermal conductivity of 29 w/(m·K).

2.1.2 Energy balance of system

There are four parts of energy input and output the biogas fermentation system: the heat supplied by the heat exchange Q, the heat produced by the fermentation Q_a, the heat losses by the tank Q_b and the heat losses or added by the new materials Q_c. The diagram of energy balance for the fermentation system is shown in Figure 2.

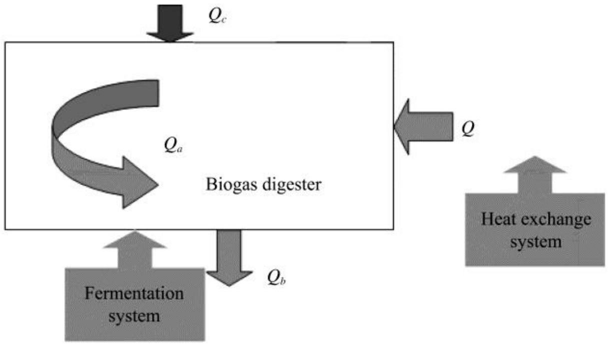

Figure 2 Energy balance of fermentation system

The energy balance of the fermentation system is given by:

$$Q = Q_a + Q_b + Q_c \tag{1}$$

Generally, the activity of the fermentation process is not strong and the temperature changes are caused by small biomass fermentation. Thus, the heat produced by anaerobic fermentation can be negligible.

The energy balance for the fermentation system yields:

$$Q = Q_b + Q_c \tag{2}$$

The heat dissipation is completed through the outer wall to the outside space for the fermentation tank. Fermentation tank is cylindrical and the surfaces of the heat dissipation are divided into two parts: two round bottoms and one cylinder wall. The cylinder in the daytime is surrounded in collector framework, and the heat loss is neglected. While the heat loss mainly happened at night. The heat losses by the fermentation tank can be expressed as:

$$Q_b = 2\Phi_B T_s + \Phi_C T_{s'} \tag{3}$$

where, Φ_B and Φ_C are the heat losses from the round bottom and cylinder wall, respectively; T_s and $T_{s'}$ are the heat dissipation time of the round bottom and cylinder wall.

In order to simplify the calculation, the following assumptions are made according to the actual situations: (1) when calculating the heat loss in the process of fermentation, all the substances (biogas and fermentation raw materials) in the digester are at the same temperatures; (2) usually, the average thermal conductivity coefficient of coating material is big, and its thickness is relatively small (often less than 1 mm). Hence, the thermal resistance of coating material can be ignored; (3) when the temperature decrease of fermentation raw material is less than 5 ℃/h for insulation structure, the temperature for the each part of raw materials changes slowly, the internal temperature field can be regarded as steady temperature field.

Based on the assumptions above, the heat losses from the round bottoms of fermentation tank can be given by:

$$\Phi_B = KA_1(t_1 - t_0) \tag{4}$$

where, K is the total heat transfer coefficient; A_1 is the heat transfer area; t_1 is the feed liquid temperature and t_0 is the environment temperature.

The total heat transfer coefficient of multilayer flat wall can be described by:

$$K = \frac{1}{\frac{1}{h_1} + \sum_{i=1}^{n}\frac{\delta_i}{\lambda_i} + \frac{1}{h_2}} = \frac{1}{\frac{1}{h_1} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{1}{h_2}} \tag{5}$$

where, h_1 is the convective heat transfer coefficient between the fermentation material liquid and the wall; h_2 is the convective heat coefficient between the air outside and the surface of fermentation tank; λ_1 and λ_2 are the thermal conductivity coefficients of stainless steel and thermal insulation materials, respectively; δ_1 and δ_2 are the thickness of the steel plate of tank and thermal insulation materials.

Because of the different environment temperatures in the daytime and nighttime, the heat losses from the round bottoms of fermentation tank are separated into two parts: the heat losses in the daytime and that in the nighttime.

The heat losses from cylinder wall can be given by:

$$\Phi_C = \frac{2r_0(t_1 - t_0)}{\frac{1}{2\pi h_1 r_0} + \frac{1}{2\pi\lambda_1}\ln\frac{r_1}{r_0} + \frac{1}{2\pi\lambda_2}\ln\frac{r_2}{r_1} + \frac{1}{2\pi h_2 r_2}} \tag{6}$$

where, r_0, r_1 and r_2 are the inner radius and outer radius of fermentation tank and the thermal insulation layer radius of the outer wall, respectively.

The system is operated outdoors. There is no heat loss from the cylinder wall in the daytime due to the heat collection system surrounding the outside of the tank. The heat loss from the cylinder wall happens at night.

For this continuous fermentation system, parts of the used materials need to be discharged and the same mass of new materials needs to be added in the fermentation tank at the same time every day. New materials with the same temperature need to be heated in order to maintain the constant temperature in the fermentation tank. The heat added for the new materials can be expressed by:

$$Q_c = c_p m(t_1 - t_2) \tag{7}$$

where, c_p is the specific heat of the fermentation liquor; m is the amount of fermentation liquor added every day; and t_2 is the initial temperature of fermentation liquor added.

The amount of heat flow supplied by the coil should be given by:

$$\Phi = \frac{Q}{t} \tag{8}$$

where, t is the operation time of the system per day.

2.2 Heat exchange system

The heat exchange system is different from the heating system by the conventional solar water heater. It is connected to the collecting system. And it mainly contains two parts: the connecting water pipe and heat exchange coil. The connecting pipe is the end of the collecting system. There are no heat losses for the heat exchange coil because the heat exchange coil is fixed inside the digester and directly transfers heat to fermentation liquid. Hence, the energy balance analysis on the heat exchange system mainly includes three parts: the heat flow Φ supplied by heat exchange coil for the digester, the heat flow Φ_0 supplied by collecting system for connecting water pipe, and the heat losses Φ_2 from the connecting pipe. The diagram of the heat exchange system energy balance is shown in Figure 3.

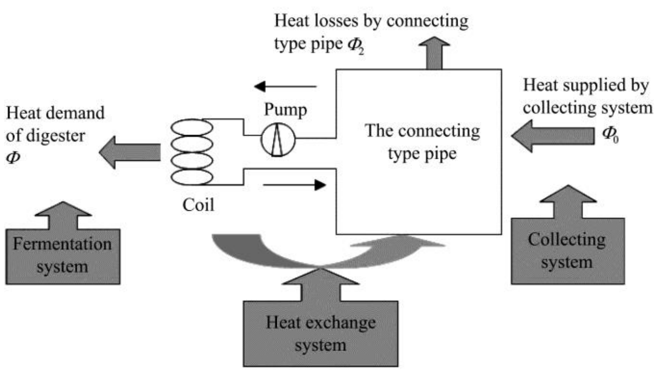

Figure 3 Energy balance of heat exchange system

The energy balance for the heat exchange system can be expressed as:

$$\Phi_0 = \Phi + \Phi_2 \tag{9}$$

The mechanical diaphragm metering pump is selected to be used in the heat exchange system and its key parameters are shown in Table 1.

Table 1 Parameters of diaphragm metering pump

Parameters	Values
Pump head material	PVC
Power /W	60
Rotate speed /r min^{-1}	1350
Flow rate /L h^{-1}	30
Rated pressure /Mpa	0.4

The heat transfer area of the heat exchange coil can be given by:

$$A_2 = \frac{Q}{K_2 \Delta t_m} \tag{10}$$

where, K_2 is the total heat transfer coefficient, and Δt_m is the average heat transfer temperature difference.

The length of the heat exchange coil can be described as:

$$L = \frac{1.5A_2}{\pi d_1} \tag{11}$$

where, d_1 is the inner diameter of the heat exchange coil.

2.3 Heat collecting system

2.3.1 Energy balance for heat collecting system

The energy balance for the heat collecting system mainly includes: the heat flow (Φ_0) which is supplied to the connection type pipe by the heat collecting system, the quantity of unit area of the sun point-blank (Φ_I), the average height angle of the sun (α), the light transmittance of glass (η_1), the absorbance of absorbing coatings (η_2), and the efficiency of heat pipe (η_3). The energy balance diagram is shown in Figure 4.

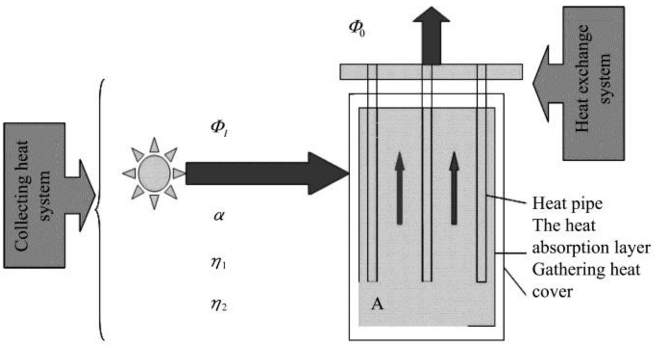

Figure 4 An energy balance model for the heat collecting system

The energy balance for the heat collecting system can be given by:

$$\Phi_0 = \Phi_I \mathrm{A} \eta_1 \eta_2 \cos\alpha \tag{12}$$

2.3.2 Selection of working fluid and materials for the heat pipe

The compatibility is a key significance in the application of heat pipe. Only high quality heat pipe can guarantee the stability of the heat transfer performance, long term usage, and the possibility of industrial application. By selecting the compatible working fluid and the shell materials, the heat pipe can effectively run for a long period of time[22].

The heat pipe in this system works at the temperature range of 20℃-80℃, which belongs to the normal temperature heat pipe. The heat pipe working fluids under normal temperature are shown in Table 2.

Table 2 Working fluids of heat pipe under normal temperature

Working fluids	Working temperature range/ ℃	Compatible shell materials
Hexane	0-100	Brass and stainless steel
Acetone	0-120	Aluminum, copper and stainless steel
Ethanol	0-130	copper and stainless steel
Methanol	0-130	copper, stainless steel and carbon steel
Toluene	0-290	Stainless steel, low carbon steel and low alloy steel
Water	30-250	Copper and carbon steel

The heat pipe is preliminarily designed to work within the temperature range of 20℃-80℃ in the stagnation heat collecting system. The cooling temperature and the fermentation temperature both end at 30℃ in the winter time. The lowest work temperature of heat pipe is designed to be 20℃-40℃. Brass is adopted as the shell material for the heat pipe. The physical and chemical properties including several kinds of working fluids for heat pipe under normal temperature are shown in Table 3.

Table 3 Physical and chemical properties of working fluids for heat pipe

Working fluids	Specific heat capacity /kJ (kg k)$^{-1}$	Boiling point / ℃	Latent heat of vaporization/kJ kg^{-1}
Methanol	1.86	64.6	1126
Acetone	2.21	56.1	524.6
Ethanol	2.71	78.4	819.5
Hexane	1.59	80.7	333.4

Due to the latent heat of vaporization is relatively high for methanol, which is selected as the working fluid of heat pipe. The performance parameters of the designed heat pipe are shown in Table 4, and the heat pipe structure is shown in Figure 5.

Table 4 Parameters of the designed heat pipe

Parameters	Values
Nominal diameter /mm	20
Wall thickness /mm	1
Working fluid	Methanol
Materials	Brass
The total length /mm	800 mm
Temperature of hot end /℃	40
Temperature of cooling end /℃	35
Power /W	80
Efficiency	70%

Figure 5 Structure of the designed heat pipe

In order to keep at least one surface absorbing the sunlight in the daylight, four surfaces are arranged lighting device for the heat collecting system. The four surfaces are the same; however, only one of the surfaces is used to absorb the sunlight. The heat pipe works when the sun beats down on one of the surfaces, and the other three endothermic layers do not work. The efficiency of the heat pipe facing the sun is higher and the amount of heat transmission will account for 95% while the other three heat pipes accounts for 5%. Each surface is installed with the same number of heat pipes, which can be calculated by:

$$n = \frac{0.95Q_0}{0.9P_h} \tag{13}$$

where, P_h is the power of heat pipe.

The total heat pipes are given by:

$$N = 4n \tag{14}$$

2.3.3 Heat collecting area

The solar selective absorption coating is made by the coating spraying method. This method is simple in process and it is commonly used under medium and low temperature conditions because of the pyrolysis of binder at higher temperature[23].

The solar radiation intensity in Zhengzhou (the capital of Henan province, China) is shown in Table 5[24]. The average solar altitude in winter of Zhengzhou is 48 degrees.

Table 5 Solar radiation intensity of Zhengzhou area[24]

Parameters	Winter	Spring	Summer	Autumn
Intensity of the solar energy/MJ m^{-2}	222.3	432.63	680.16	426.88
Number of sunny days every month/d	18	22	25	22
Number of sunlight every day/h	7	8	9	8
Daily solar radiation/W m^{-2}	490.8	682.81	839.5	673.73

The heat collecting area can be given by:

$$A = \frac{\Phi_0}{\Phi_I \eta_1 \eta_2 \cos\alpha} \tag{15}$$

2.4 Whole system

The new biogas fermentation system by solar heat pipe heating is shown in Figure 6. The experiment will be completed based on this system.

Figure 6 Diagram of the new biogas fermentation system by solar heat pipe heating

2.5 Technology and economy of the system

The heat supplied by heat exchange system to the fermented liquid is converted into standard coal to reflect the economy of the system. The conditions in winter and spring are considered, respectively.

The conversion of standard coal is given by:

$$m = \frac{Q_0}{q_0 \eta_4 \eta_5} \tag{16}$$

where, Q_0 is the collected heat by the heat exchange system in winter or spring; q_0 is the calorific value of standard coal; η_4 is the efficiency of heating water by standard coal, and η_5 is the heat transfer efficiency of heat exchanger.

3 Materials and methods

3.1 Experimental materials

In order to further verify the actual operation effect of biogas fermentation system by solar heat pipe heating, the fermentation experiment was carried out into the spring time to test the state of biogas production. The fermentation raw materials, cow manure is from Mao village experimental base of Henan Agricultural University and the inoculum is from laboratory fermentation broth. The concentration of fermentation raw material is 6%, the ratio of carbon and nitrogen is of 25:1, the volume of the inoculum accounts for 30% of the fermentation raw materials, and that of the fermentation liquor after adding water accounts for 85% of the fermentation tank. The ratio of the carbon and nitrogen in cow manure conforms to the requirements of the best carbon and nitrogen ratio of the fermentation liquid, and it is not necessary to adjust with other raw materials. The cow manure of 40 kg, the biogas slurry of 40 L and the water of 105 L are used to prepare for the biogas fermentation liquor of 175 L.

3.2 Test methods

The gas component content was measured with gas chromatograph which was produced by Agilent. The quantitative gas inlet ring of 250 μL was adopted. The temperatures of the detector, the chromatographic column and the injection port are set to be 150 ℃, 80 ℃ and 60 ℃, respectively. The relationship between the methane content y_1 (%) and the peak area x_1 is described by: y_1=0.0031x_1+2.5029, while the relationship between carbon dioxide y_2 (%) and peak area x_2 is depicted by: y_2=0.0147x_2 - 10.6. The methane peak time is of 0.6 s, while it is 1.2 s for carbon dioxide[25].

3.3 Experimental process

The experiment was carried out in the third living region of Henan Agricultural University. The system started working on May 8th, 2013, and ran for half a month. The methane yields, biogas composition and temperature variation of each sample point were recorded every day during the operation time. The recording time was from 9 am to 5 pm, the temperatures of T_1, T_2, T_3, T_0 and E were recorded every 30 min respectively. The yields of biogas, methane and carbon dioxide content were analyzed every day.

4 Experimental results and discussion

The environmental conditions between May 9th and May 20th are shown in Table 6, while the measured temperatures of the system are described under Table 7.

Table 6 Environmental conditions

Parameters	Dates and weather											
	9	10	11	12	13	14	15	16	17	18	19	20
	LR	S	S	S	S	C	C	C	C	LR	S	S
MI	63	1107	1189	1241	1257	717	147	644	217	142	917	1057
AI	55	976	1024	1088	1104	428	77	315	118	99	794	912
HT	26	31	33	35	36	34	33	33	32	29	31	33
AT	23	27	29	30	31	30	29	30	28	26	28	30

Notes: MI=The maximun illuminance (*200000 lux), AI=Average illuminance (*200000 lux), HT=The highest temperature / ℃, AT=Average temperature / ℃; LR= Light rain, S=Sunny, C= Cloudy.

Table 7 Temperatures of system

Temperatures		Dates											
		9	10	11	12	13	14	15	16	17	18	19	20
T_1 / ℃	Initial	21.7	21.3	26.2	31.3	34.9	36.9	36.0	35.0	34.3	33	32.6	35.3
	Eventual	21.5	26.4	31.7	35.3	37.5	37.4	36.2	35.2	33.9	33.5	36.1	38.2
	Increase	−0.2	5.1	5.5	4	3.6	0.5	0.2	0.2	−0.4	0.5	3.5	2.9
T_2 / ℃	Initial	21.6	21.5	26.8	32.2	35.3	37.5	38.0	36.9	36.4	34.7	33.1	36.2
	Eventual	21.4	27.7	32.4	36.3	38.9	39.1	37.5	37.4	35.6	33.5	36.6	38.8
	Increase	-0.2	6.2	5.6	4.1	3.6	1.6	−0.5	0.5	−0.8	−1.2	3.5	2.6

The biogas yields and the average fermentation temperature are depicted in Figure 7. Figure 7 showed that the average fermentation temperature increased first and then decreased with the fermentation time, which exhibited a highest value of fermentation temperature under the conditions investigation. The decrease of fermentation temperature was due to the cloudy weather on May 14th, 15th 16th and 17th. The fermentation temperature of the system on a sunny day rose by 4.5℃ during the daytime, however, it decreased by 0.8℃ at night time. In a cloudy day, the temperature also decreased by 0.4℃ during the daytime.

As shown in Figure 7, the biogas yields increase with the time and when it kept a stable value. The yields were about 70 L every day in the stable phase. The increase of biogas yields is related to the rise of the average fermentation temperature. The increased average fermentation temperature could help methane bacteria grow better, which leads to a rapid decomposition of the protein in cow manure, thus the yields of biogas increased. The biogas yields reduced slightly, because the average fermentation temperature on May 14th, 15th, 16th and 17th decreased.

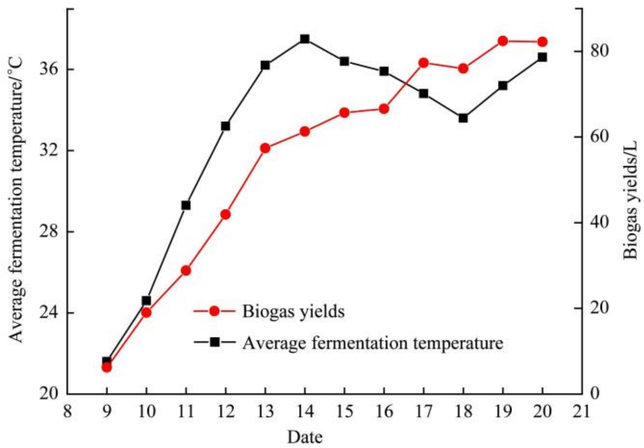

Figure 7 Biogas yields and average fermentation temperature

Methane content and carbon dioxide content of biogas are shown in Figure 8. The methane content raised with the fermentation time and then kept a stable value as described in Figure 8. The content of methane reached 70%. The content of carbon dioxide firstly increased, then decreased and finally kept a stable value (about 17%). These variations are related to the activity of methane bacteria and hydrolyzing of fermentation raw materials. For the initial time of fermentation, the activity of methane bacteria is low in the new surroundings. Hence, the content of methane is low. When the methane bacteria has adapted to its surroundings, the activity was better and the content of methane rose. Simultaneously, the fermentation raw materials hydrolyze and quantity of carbon dioxide is produced. When the process of hydrolyzing completed, the content of carbon dioxide kept stable.

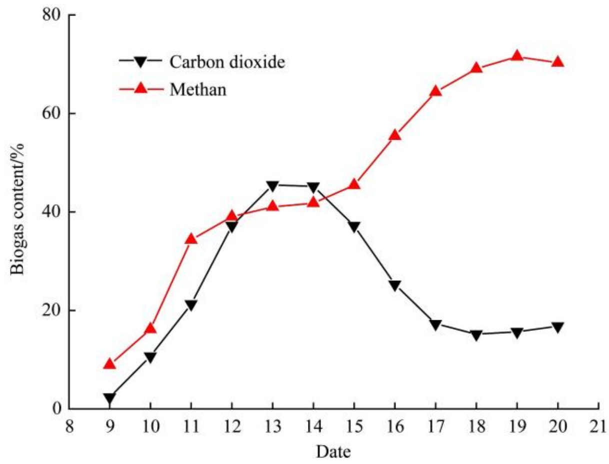

Figure 8 Methane content and carbon dioxide content of biogas

From the above results, this new biogas fermentation system by solar heat pipe heating can realize continuous heating and produce biogas normally.

5 Technical and economic analysis of the system

In order to investigate the economy properties of the newly designed system, following assumptions are made: the environment average temperature in the winter season during the day is of 8℃, this system can run up to 20 days per month, the efficiency of heating water by standard coal is 30% and the heat transfer efficiency by the heat exchanger is 40%.

According to the Equation (16), this new biogas fermentation system by solar heat pipe heating in the winter can save standard coal of 40 kg. Likewise, it can save standard coal of 80 kg in the spring.

6 Conclusions

A new biogas fermentation system by solar heat pipe heating was designed and the preliminary experimental research on this system was completed, with cow manure as raw material. The main conclusions were obtained as follows:

1) When the initial temperature of this new system was 21.7℃, the system fermentation temperature rose every day under the normal operation. With the rising of fermentation liquid temperature, this gradient will gradually become smaller. The stable fermentation temperature can reach 38℃. The fermentation temperature decreased to an average value of 33.5℃ due to the continuous cloudy day.

2) Within a certain range, the biogas yields increased with the fermentation time. It might keep a stable value of about 70 L a day. The methane content increased with the fermentation time, and finally it was stabilized at around 70%. The carbon dioxide content firstly raised, then decreased and finally kept at a stable value with fermentation time.

3) When this system is operated in a sunny day, the fermentation temperature improved by 5℃ using the heat collecting system, although it decreased by 0.6℃ at night.

4) This new biogas fermentation system by solar heat pipe heating exhibits excellent market prospects from energy and economic analysis.

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