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Design and Implementation of Parabolic Trough Concentrator Heating Anaerobic Reactor

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Abstract: For an anaerobic fermentation system, the temperature is one of key factors which affect the efficiency of biogas production. A parabolic trough concentrator (PTC) was used as the heat source for an 8 m^3 underground anaerobic digester. To improve the efficiency of concentrating solar collectors and the biogas productivity of traditional anaerobic fermentation system, the sizes of important components in the digester were determined, and the energy balance was also calculated. Moreover, the angle change of solar concentrator in Yangling was counted, the angle of the collector during one year was optimized, and the inclination angle and installation method of the concentrator bracket were also designed. It was found that feed heat loss (16 077.31 kJ/d) and wall heat loss (23 180.01 kJ/d) were the two main heat loads in this system. The key parameters of PTC were determined: the size of aperture was 2.4 m, the focal distance was 0.6 m, the area of collector was 4.16 m^2, and the diameter of collector pipe was 0.016 8 m. In addition, the heat transfer of anaerobic reactor was simulated through Fluent software. The simulation results revealed that interior temperature in the digester could be maintained at 35℃. A PTC-based anaerobic digester with similar parameters of simulation model was designed to verify the simulation effect. The experiment results indicated that the temperature range of material liquid in the reactor could be kept at 33.6 ~ 35.8℃, approximately consistent with the Fluent simulation. The results in this study provide a new solution for efficient and low-cost biogas fermentation device.

Key words: anaerobic reactor; parabolic trough concentrator; steady simulation

0 Introduction

Biogas occupies an very important position in China's rural energy market[1]. Promotion of the use of biogas in rural areas plays a positive role in recycling rural organic waste, meeting farmers' demand of biogas and improving the in living conditions[2-3]. However, due to low fermentation temperature and large fluctuation of environmental temperature etc., problems regarding the production instability of the rural household biogas reactors and non gas production in cold winter of the north of China generally exist[4-7], which have seriously hampered its application. Temperature is one of key factors affecting the efficiency of biogas production; combining the use of solar energy resources with anaerobic digestion technology through heating the reactors by solar energy to increase the temperature of the heating system of biogas fermentation, is a low-cost, efficient and practical heating method, and also is an effective way to improve the quality and efficiency of biogas fermentation device[8].

Parabolic through concentrator (PTC) using the reflection principle has greatly improved the energy density of the solar light, and has been extensively applied in industrial and agricultural production and human life[9]. Put into operation in 2007 in Nevada, the United States, PTC power plants annually produce 64 million kW·h electricity for 140,000 families. PTC has also been utilized in production and life field of heating, air conditioning, desalination of sea water etc[10].

In this study, using PTC as heating source to heat

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biogas fermentation device system of widely used 8 m^3 underground anaerobic reactor by farmers, we designed the corresponding key parameters of PTC, and simulated the overall heat transfer and verified it by experimental results. We aimed at improving the efficiency of concentrating solar energy of PTC and the performance of traditional anaerobic fermentation system to provide a new solution for efficient and low-cost biogas fermentation device.

1 System construction and PTC design

1.1 System construction and thermal balance calculation

1.1.1 System construction

The anaerobic fermentation system heated by PTC consists of PTC unit, heat storage water tank, circulating water pump, temperature control instrument, electrical heating device and spiral heat exchanger (Fig. 1). The anaerobic fermentation system is 8 m^3 underground anaerobic reactor, the heating device is PTC, which provides the required heat of the anaerobic reactor[11].

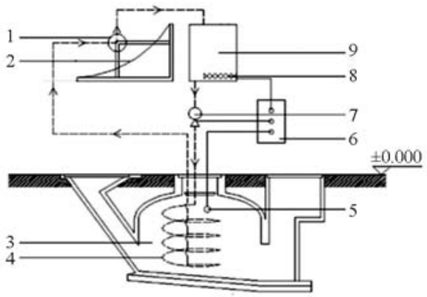

Fig. 1 Structure diagram of fermentation device by PTC heating

1. Vacuum heat collecting pipe 2. Heat collecting plate 3. Anaerobic reactor 4. Spiral heat exchanger 5. Temperature sensor 6. Circulating water pump 7. Temperature control instrument 8. Electric heating device 9. Heat storage water tank

1.1.2 Thermal balance calculation

The heat loss of the anaerobic reactor is mainly from feed heat loss Q_j, fermented materials heat loss Q_{loss} and gas heat loss Q_q in reactor[12]. The heat of the biogas reactor is mainly provided by PTC Q_{solar}, the auxiliary heat source Q_e and the internal energy of fermented materials Q_r (Fig. 2). Due to gas heat loss Q_q and the internal energy of fermented materials Q_r are small and negligible ($Q_q = 0$, $Q_r = 0$), the thermal balance equation of the whole system is

$$\rho_m v_m C_m \frac{dT_m}{dt} = Q_e + Q_{solar} - Q_{loss} - Q_j \tag{1}$$

in which, ρ_m is the density of material in reactor, kg/m^3; v_m is the volume of material in reactor, m^3; C_m is the specific heat capacity of material in reactor, kJ/(kg·K); T_m is the temperature of material in reactor, ℃; t is the time, s.

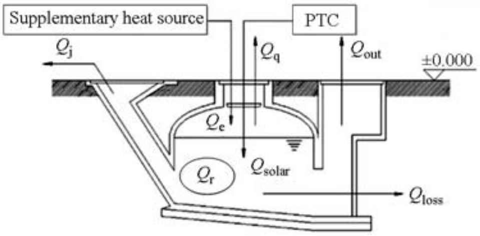

Fig. 2 Schematic presentation of thermal balance of anaerobic reactor

To achieve the thermal balance of anaerobic fermentation system, so

$$\rho_m v_m C_m \frac{dT_m}{dt} = 0$$

It is assumed that PTC can providethe enough heat energy without the auxiliary heat source, the Eq. (1) is simplified to

$$Q_{solar} - Q_{loss} - Q_j = 0 \tag{2}$$

1.1.2.1 Calculation of feed heat loss Q_j

The heat consumption by feed entering the reactor within a day to achieve a constant temperature is[13]

$$Q_j = C_m M (t_d - t_s) \tag{3}$$

in which, M is the daily amount of feed into the reactor, kg/d; t_d is the average temperature of material in biogas reactor, assuming that the system can make material temperature maintained at about 35 ℃; t_s is the temperature of fresh feed into the reactor, assuming it is the same with ambient temperature t_a, so $t_a = t_s = 5$ ℃.

For 8 m^3 underground anaerobic reactor, the amount of dry material daily treated is 12.8 kg, the mass fraction of feed used is 10%, so the daily amount of fresh liquid feed put into the reactor is

$$M = 12.8 \text{ kg}/10\% = 128 \text{ kg}$$

The specific heat capacity of feed can be approximated as the specific heat capacity of water, $C_m = 4.1868$ kJ/(kg·K). It is calculated that $Q_j = 160\,77.31$ kJ/d.

1.1.2.2 Calculation of device heat loss Q_{loss}

(1) Heat transfer coefficient

Heat transfer coefficient[14] of the reactor in soil is

$$U = \frac{1}{\frac{1}{a_1} + \frac{\delta}{\lambda} + \frac{1}{a_2}} \tag{4}$$

in which, a_1 is the heat transfer coefficient of inner surface, 336 W/(m^2·K); a_2 is the heat transfer coefficient of outer surface, 0.47 W/(m^2·K); δ is the thickness of reinforced concrete layer, 0.2 m; λ is the thermal conductivity coefficient of the reinforced concrete layer, 1.543 W/(m^2·K). Then U = 0.442 5 W/(m^2·K).

(2) The size of reactor

Through calculating of the ratio of reactor cover radius and reactor bottom radius to ensure the strengthof the reactor and minimum the surface area of heat transfer, the required size of the reactor is[15]

$$f_1 = \frac{2}{5}R \tag{5}$$

$$f_2 = \frac{2}{7}R \tag{6}$$

The total volume

$$V = 0.36\pi R^3 + \pi R^2 h \tag{7}$$

The total surface area

$$S = \frac{2V}{R} + 1.52\pi R^2 \tag{8}$$

in which, R is the radius of the cylindrical fermentation reactor, m; f_1 is the height from the top of the reactor to the upper cover of the cylindrical reactor, m; f_2 is the height from the bottom of the reactor to the lower cover of the cylindrical reactor, m. By derivation of the Eq. (8), the R corresponding to the minimum surface area can be calculated, in this case $R = 1.188$ m, the total surface area of reactor S = 20.21 m^2. The geometrical size of 8 m^3 reactor can be obtained as shown in Fig. 3.

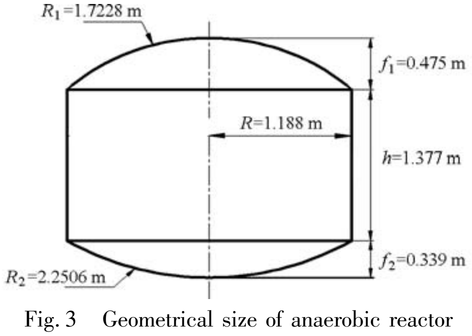

Fig. 3 Geometrical size of anaerobic reactor

(3) The fermented materials heat loss Q_{loss}

After obtaining the heat transfer coefficient and the surface area, the heat loss can be determined

$$Q_{\text{loss}} = US(t_d - t_a) = 23\,180.01 \text{ kJ/d} \tag{9}$$

so, $Q_{\text{solar}} = 39\,257.32$ kJ/d.

1.2 Design and calculation of PTC

1.2.1 Design of heat storage tank

The heat storage tank is mainly used to reserve a certain amount of heat energy, which can provide heat for the fermentation device when the weather or environmental temperature fluctuates drastically, thereby to stabilize the fermentation temperature of the liquid feed and ensure the normal operation of the fermentation device[16]. Without considering other heat loss, the formula of calculating the minimum volume of heat storage tank is

$$V_{\min} = \frac{Q_{\text{solar}}}{c\rho(t_{\text{guan}} - t_{\text{liao}})} \tag{10}$$

in which, $V_{\min}$ is the minimum volume of heat storage tank, m^3; c is the heat capacity of water, kJ/(kg·K); ρ is the water density, kg/m^3; t_{guan} is the water temperature in the spiral pipe, ℃, i. e. the preset water temperature at the outlet of storage tank 75 ℃; t_{liao} is the water temperature at the outlet of spiral tube, i. e. the preset temperature of liquid feed 35 ℃.

After calculation, $V_{\min} = 0.23$ m^3.

1.2.2 Calculation of PTC surface area

The formula of calculating PTC surfacearea is[17]

$$A_c = \frac{Q_{\text{solar}} f_0}{I_t \eta_{cd}(1 - \eta_c)} \tag{11}$$

A_c is the PTC surface area, m^2; I_t is the local daily amount of solar radiation, 14.145 MJ/(m^2·d); f_0 is solar fraction, 0.6; η_{cd} is the PTC thermal efficiency, 0.5; η_c is the heat loss rate of pipe and heat storage tank, 0.2.

Calculated $A_c = 4.16$ m^2.

1.2.3 Design of paraboloid

Sunshine through the paraboloid apertur of PTC (i. e. the opening width of paraboloid b, in Fig. 4), enters PTC. Therefore its aperture size decided the total input energy of PTC. The concentration degree was positively correlated with the collector efficiency[18]. For the circular tube-type collector, the maximum value of the concentration ratio K is 68.4 when the relative aperture n is 4. The determined aperture size b is 2.4 m. Focal distance f is 0.6 m (b/n), the minimum diameter of collector is

$$d_{\min} = 2\left(f + \frac{1}{4f}\frac{b^2}{2}\right)\sin\frac{D}{2} \tag{12}$$

in which, D is sun path angle, 0.53°.

So $d_{\min} = 0.0168$ m.

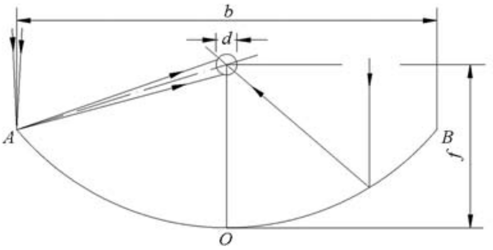

Fig. 4 Concentration efficiency of PTC

1.2.4 Design of inclination of collector angle

When the sun light and the paraboloidaperture is vertical, the reflecting surface received the most direct sunlight, the optimal angle of the concentrator is

$$b_1 = \tau - \delta_1 \tag{13}$$

in which, τ is the local latitude, the latitude of Yangling area (34°16′N); b_1 is the optimal angle of concentrating collector; δ_1 is the declination.

By calculation, the average monthly solar declination of 2012—2014 is shown in Fig. 5.

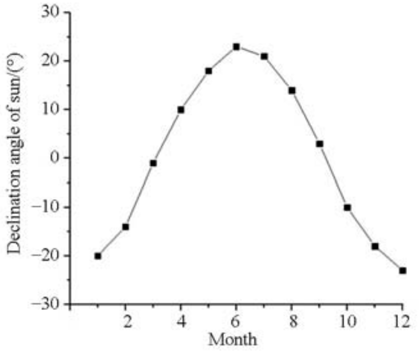

Fig. 5 Statistic result of average solar declination in recent three years

By the Eq. (13), the changes of heat collector angle in one year can be drawn and shown in Fig. 6.

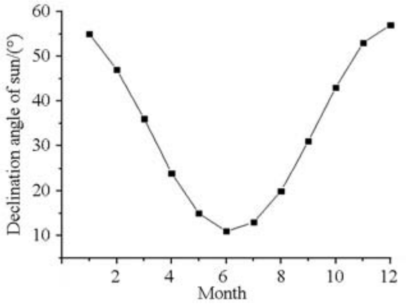

Fig. 6 Changing curves of heat collector angle

1.2.5 Inclination angle and bracket

In the controlling design aspect of inclination angle, the handle connecting rod is longitudinally grooved, the positioning plate is horizontally drilled; when the handle is turned a certain angle and needs to be fixed, the handle and the positioning plate are connected through the slot and the articulation hole bolt, GB27—88 series hexagon head bolts are selected; the handle and the rotating parabolic mirror are positioned by bolt shear capacity and friction force. The two extreme positions of the handle are shown in Fig. 7, representing the bracket angle in December and June, respectively. The certain angles from January to May and from July to November are among the two abovementioned angles.

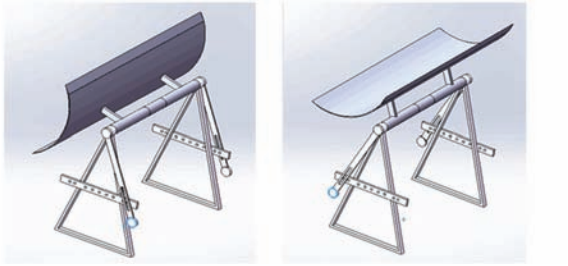

Fig. 7 Model of PTC

2 Simulation and experimental verification of heat transfer system

Fluent and Gambit software were used to simulate the heat transfer in PTC heating anaerobic reactor, in order to confirm the rationality of the designed system.

2.1 Model construction

The water temperature of the reactor inlet is 75 ℃, and it is assumed that, ① the top 1/4 of the reactor is gas part. ② The heat dissipation effect of gas-liquid interface is the same as that of the wall surface. ③ The heat produced by the fermented materials and carried away by gas are ignored. ④ The default inlet temperature is constant[19]. The resulting reactor model is shown in Fig. 8. Because of the huge difference between the geometrical size of the pipe and the reactor, it is necessary to partition the liquid material area and to simplify the grid. The liquid material area is divided into the near tube zone and the far tube zone, the interface is set up in the Gambit, and is confirmed in the Fluent.

2.2 Grid division

Due to the outstanding advantage of the tetrahedral mesh which can adapt to the more complex geometric structure, the Tgrid tetrahedral model is chosen[20]. According to the different size, the unit grid size of the heat exchange tube is determined as 7, the grid number is 298 464; the unit grid size of the near tube liquid material zone is determined as 20, the grid

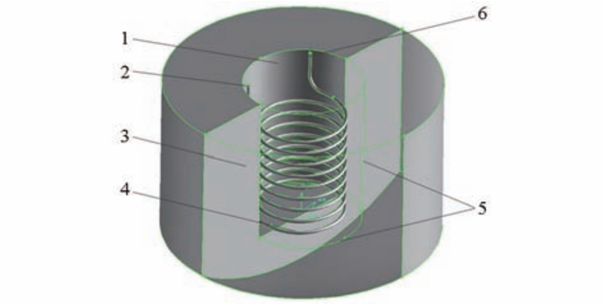

Fig. 8 Geometrical model of reactor

1. The near tube liquid material zone 2. Hot water inlet 3. The far tube liquid material zone 4. Heating tube 5. Interface 6. Hot water outlet

number is 1 672 622; the size of the far tube liquid material zone is determined as 40, the grid number is 894 413. The model of three unit grids are shown in Fig. 9.

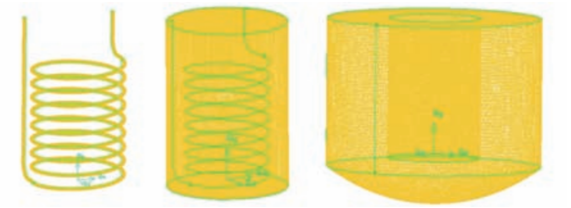

Fig. 9 Grid of model

2.3 Simulation result

The diameter of the vacuum tube of the collector is 0.016 8 m, and the inner diameter of the heat exchange tube in the reactor is 0.03 m. To ensure the liquid material in anaerobic reactor is run at about 35 ℃ throughout the year in Yangling, Shaanxi Province, the external heat source is necessary at least seven months, and the inlet temperature of the heat exchange tube is not less than 50 ℃. The inlet flow rate is set as 150 L/h and is approximately 0.06 m/s in terms of inlet velocity. Through optimizing the system design, the working temperature of fluid is more than 50 ℃. Based on the energy balance calculation, and taken into account the heat loss of feed and device, the heat loss of the reactor wall is 22.5 W/m^2, and the heat dissipation form is set as Heat Flux.

Through the simulation calculation, the heat transfer efficiency of the heat exchange tube to the reactor is obtained under steady state conditions. The working medium in the spiral heat exchanger obtaining energy from PTC, has very excellent heating effect on the liquid feed in the reactor, and the feed temperature can be maintained at about 35 ℃.

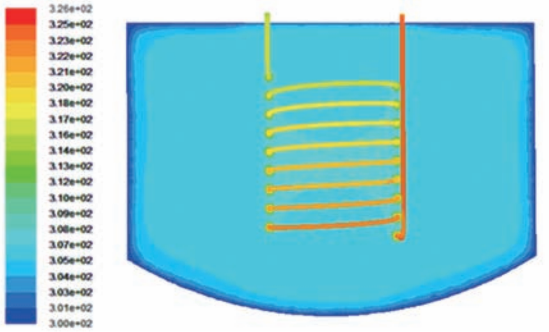

Fig. 10 Simulation result of PTC heating anaerobic reactor

2.4 Experimental verification

In November 25, 2015, the experiment was carried out in the household biogasreactor of Tracy Ditch, Yangling, in Shaanxi Province to verify the simulation result. The test equipment includes: 4.2 m^2 PTC, 0.25 m^3 heat storage tank, 8 m^3 underground anaerobic reactor, circulating water pump, spiral-tube heat exchange and temperature sensor (Fig. 11). After five days, the feed temperature in the reactor tends to be stable, the test results of November 30 are shown in Fig. 12, the lowest outdoor temperature is 0.1 ℃, the highest outdoor temperature is 11.2 ℃; the lowest temperature of the solar hot water in the heat storage tank is 37.2 ℃, and the highest temperature is 78.4 ℃; the lowest temperature of liquid feed in anaerobic reactor is 33.6 ℃, the highest temperature is 35.8 ℃.

Fig. 11 Photo of PTC heating anaerobic reactor

1. Underground anaerobic fermentation system 2. PTC 3. Heat storage tank

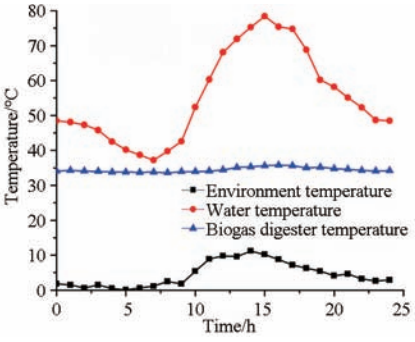

Fig. 12 Variations of water temperature, environment temperature and biogas digester temperature

The test results show that the PTC system possessing the similar parameters with the design, can provide heat energy for the 8 m^3 underground anaerobic reactor, which can keep the temperature of the liquid feed in the reactor at (34.7 ± 1.1)℃, and the Fluent simulation results is basically consistent with the test results.

3 Conclusions

(1) The heat loss of feed and fermented materials are the two main loads of the reactor, for anaerobic reactor system heated by PTC, the values of the two loads are 160 77.31 kJ/d and 231 80.01 kJ/d, respectively.

(2) When PTC aperture b is 2.4 m, the focal distance f is 0.6 m, the diameter of the collector tube is 0.016 8 m, PTC heating anaerobic reactor system can collect the maximum energy.

(3) Through preliminary computer simulation and experimental verification, the results show that PTC has very excellent heating effect on the liquid feed in the reactor, and the feed temperature can be maintained at about 35 ℃.

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槽式抛物面太阳能聚光集热器供热厌氧反应器研究

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3.农业部农村可再生能源开发利用西部科学观测实验站,陕西杨凌 712100)

摘要: 应用能量密度较高的槽式抛物面太阳能聚光集热器(PTC)为厌氧反应器提供热源,确定装置中重要单元的尺寸,并进行了反应器内部能量平衡的计算,得出 8 m^3的地下厌氧反应器内最大 2 处负荷分别为进料热损失与发酵物料散失热量,分别为 16 077.31 kJ/d 和 23 180.01 kJ/d。通过计算得出相应的聚光集热器的关键参数,确定光孔宽度 b 为 2.4 m,焦距 f 为 0.6 m,集热板面积为 4.16 m^2,集热管直径为 0.016 8 m。应用流体力学模拟软件 Fluent 对反应器内整体的传热效果进行模拟,仿真结果表明反应器内料液温度可维持在 35℃左右。采用与设计参数相近的 PTC 系统和厌氧反应器进行试验验证,厌氧反应器内料液温度保持在 33.6 ~ 35.8℃,与 Fluent 仿真结果基本吻合。

关键词: 厌氧反应器; 太阳能聚光集热器; 稳态模拟

中图分类号: S216.4; TK11^{+}2　　**文献标识码:** A　　**文章编号:** 1000-1298(2016)07-0202-06

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Abstract: For an anaerobic fermentation system, the temperature is one of key factors which affect the efficiency of biogas production. A parabolic trough concentrator (PTC) was used as the heat source for an 8 m^3 underground anaerobic digester. To improve the efficiency of concentrating solar collectors and the biogas productivity of traditional anaerobic fermentation system, the sizes of important components in the digester were determined, and the energy balance was also calculated. Moreover, the angle change of solar concentrator in Yangling was counted, the angle of the collector during one year was optimized, and the inclination angle and installation method of the concentrator bracket were also designed. It was found that feed heat loss (16 077.31 kJ/d) and wall heat loss (23 180.01 kJ/d) were the two main heat loads in this system. The key parameters of PTC were determined: the size of aperture was 2.4 m, the focal distance was 0.6 m, the area of collector was 4.16 m^2, and the diameter of collector pipe was 0.016 8 m. In addition, the heat transfer of anaerobic reactor was simulated through Fluent software. The simulation results revealed that interior temperature in the digester could be maintained at 35℃. A PTC-based anaerobic digester with similar parameters of simulation model was designed to verify the simulation effect. The experiment results indicated that the temperature range of material liquid in the reactor could be kept at 33.6 ~ 35.8℃, approximately consistent with the Fluent simulation. The results in this study provide a new solution for efficient and low-cost biogas fermentation device.

Key words: anaerobic reactor; parabolic trough concentrator; steady simulation

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引言

沼气在中国农村能源市场占据重要地位[1]，农村沼气的推广应用对循环利用农村有机废弃物、满足农民燃气需求、改善农民居住环境起到了积极作用[2-3]。然而，由于发酵温度低、受环境温度波动影响大等原因，农村户用沼气池产气不稳定、北方寒冷地区冬季不产气的问题普遍存在[4-7]，严重制约了推广应用。温度是影响沼气池产气率的重要因素，利用太阳能集热器收集太阳能加热沼气池，可将太阳能资源利用与厌氧消化技术相结合，为沼气发酵系统加热增温，是一种省维护、效率高、经济实用的增温方法，是沼气发酵装置提质增效的有效途径[8]。

槽式抛物面太阳能聚光集热器（Parabolic trough concentrator，PTC，以下简称聚光集热器）应用反射原理大大提高了太阳光能量密度，在工农业生产和人类生活中得到了很好应用[9]。投产于 2007 年的美国内华达州 PTC 发电厂每年生产 6 400 万 kW·h 电能，供 14 万户家庭使用。PTC 还主要应用于采暖、空调、海水淡化等生产和生活领域[10]。

本研究构建以聚光集热器为热源的沼气发酵装置系统，针对农户广泛应用的 8 m^3 地下厌氧反应器，设计与之配套的聚光集热器关键参数，并对系统整体传热效果进行计算机仿真和试验验证。旨在提高聚光集热器的集热效率和传统沼气发酵系统厌氧消化效能，为高效低成本的沼气发酵装置提供新的解决方法。

1　系统构建与 PTC 设计

1.1　系统构建与热平衡计算

1.1.1　系统构建

聚光集热器供热厌氧反应系统由 PTC 集热单元、储热水箱、循环水泵、温度控制仪、电加热装置和螺旋管换热器组成（图 1）。厌氧反应系统为容积 8 m^3 的地下厌氧反应器，加热装置为 PTC 集热系统，为厌氧反应器提供所需热量[11]。

1.1.2　热平衡计算

厌氧反应器的热损失主要为进料热损失 Q_j、池中发酵物料散失的热量 Q_{loss}、池中气体散失的热量 Q_q[12]。沼气池的热量主要来自于太阳能集热器提供的热量 Q_{solar}、外加辅助热源的热量 Q_e 以及发酵物料的内能 Q_r（图 2）。由于气体散失的热量 Q_q 和发酵物料的内能 Q_r 较小可忽略不计（令 $Q_q=0$，$Q_r=0$），则整个系统的热量平衡方程为

$$\rho_m v_m C_m \frac{dT_m}{dt} = Q_e + Q_{solar} - Q_{loss} - Q_j \qquad (1)$$

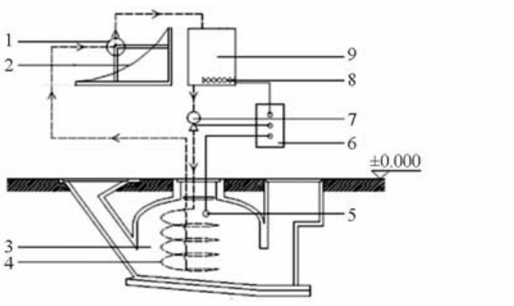

图 1　PTC 加热的沼气发酵装置结构图

Fig. 1　Structure diagram of fermentation device by PTC heating

1. 真空集热管　2. 集热板　3. 厌氧反应器　4. 螺旋管换热器　5. 温度传感器　6. 循环水泵　7. 温度控制仪　8. 电加热装置　9. 储热水箱

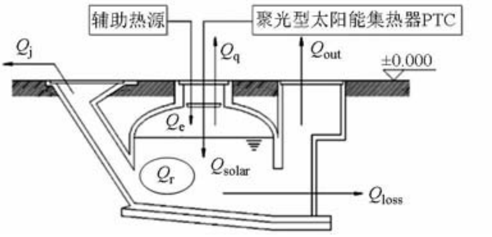

图 2　厌氧反应器热量平衡示意图

Fig. 2　Schematic presentation of thermal balance of anaerobic reactor

式中　ρ_m——反应器中物料密度，kg/m^3
v_m——反应器中物料体积，m^3
C_m——反应器中发酵物料比热容，kJ/(kg·K)
T_m——反应器中物料温度，℃
t——时间，s

若要达到系统热量平衡，令

$$\rho_m v_m C_m \frac{dT_m}{dt} = 0$$

假设此时聚光型太阳能集热器可以满足供热条件，不需辅助热源提供能量，式（1）简化为

$$Q_{solar} - Q_{loss} - Q_j = 0 \qquad (2)$$

1.1.2.1　进料热损失 Q_j 的计算

每天进入反应器的物料达到装置内物料恒定温度耗热量为[13]

$$Q_j = C_m M (t_d - t_s) \qquad (3)$$

式中　M——每日投入反应器的物料量，kg/d
t_d——沼气池内料液平均温度，℃，假设系统可以使料液维持在 35℃ 左右
t_s——投入反应器的新鲜物料温度，℃，假设与环境温度 t_a 相同，令 $t_a = t_s = 5$℃

对于 8 m^3 的厌氧反应器，设定每日处理干物质量为 12.8 kg，所采用的物料质量分数为 10%，则每日投入到反应器的新鲜料液的量为

$$M = \frac{12.8\ \text{kg}}{10\%} = 128\ \text{kg}$$

进料比热容可以近似为水的比热容，取 $C_m=4.1868\ \mathrm{kJ/(kg\cdot K)}$。故计算得到 $Q_j=16\,077.31\ \mathrm{kJ/d}$。

1.1.2.2 池中发酵物料散失热量 Q_{loss}

（1）传热系数

反应器在土壤中传热系数[14]

$$U=\frac{1}{\dfrac{1}{a_1}+\dfrac{\delta}{\lambda}+\dfrac{1}{a_2}} \tag{4}$$

式中 a_1——内表面热转移系数，取 336 $\mathrm{W/(m^2\cdot K)}$

a_2——外表面热转移系数，取 0.47 $\mathrm{W/(m^2\cdot K)}$

δ——钢筋混凝土层厚度，取 0.2 m

λ——钢筋混凝土层导热系数，取 1.543 $\mathrm{W/(m\cdot K)}$

则 $U=0.4425\ \mathrm{W/(m^2\cdot K)}$。

（2）反应器尺寸

通过池盖矢径比与池底矢径比的计算，为保证发酵罐强度和最小的散热面积，需要满足尺寸条件[15]

$$f_1=\frac{2}{5}R \tag{5}$$

$$f_2=\frac{2}{7}R \tag{6}$$

总体积

$$V=0.36\pi R^3+\pi R^2h \tag{7}$$

总表面积

$$S=\frac{2V}{R}+1.52\pi R^2 \tag{8}$$

式中 f_1——沼气罐池盖高度，m

f_2——沼气罐池底高度，m

R——沼气罐主体圆柱底面半径，m

通过对式（8）求导可求出最小表面积时对应的 R，此时 $R=1.188$ m，反应器总表面积 $S=20.21\ \mathrm{m^2}$。可得出如图 3 所示 8 $\mathrm{m^3}$ 反应器的几何尺寸。

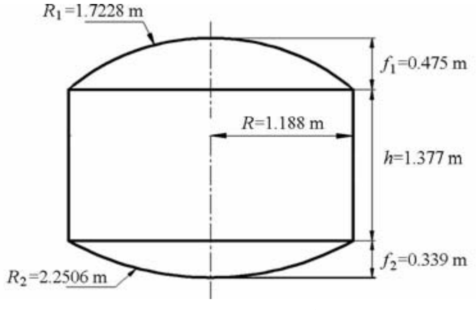

图 3 厌氧反应器几何尺寸

Fig. 3 Geometrical size of anaerobic reactor

（3）池中发酵物料散失热量 Q_{loss} 计算

传热系数与表面积确定后，即可确定

$$Q_{\text{loss}}=US(t_d-t_a)=23\,180.01\ \mathrm{kJ/d} \tag{9}$$

故 $Q_{\text{solar}}=39\,257.32\ \mathrm{kJ/d}$。

1.2 PTC 设计计算

1.2.1 储热水箱容积设计

储热水箱主要用于储备一定热量，在天气或环境温度剧烈变化时为发酵装置提供热量，进而稳定料液发酵温度，确保发酵装置正常运行[16]。在不考虑其他热损失时，储热水箱最小容积计算公式为

$$V_{\min}=\frac{Q_{\text{solar}}}{c\rho(t_{\text{guan}}-t_{\text{liao}})} \tag{10}$$

式中 $V_{\min}$——储热水箱最小容积，$\mathrm{m^3}$

c——水的比热容，$\mathrm{kJ/(kg\cdot K)}$

ρ——水的密度，$\mathrm{kg/m^3}$

t_{guan}——螺旋管内水温，℃，即储水箱出口处预设的水温 75℃

t_{liao}——螺旋管出口处水温，即料液设定温度 35℃

经计算，$V_{\min}=0.23\ \mathrm{m^3}$。

1.2.2 集热器面积计算

集热器的面积计算式为[17]

$$A_c=\frac{Q_{\text{solar}}f_0}{I_t\eta_{cd}(1-\eta_c)} \tag{11}$$

式中 A_c——集热面积，$\mathrm{m^2}$

I_t——当地日均太阳辐照量，取 14.145 $\mathrm{MJ/(m^2\cdot d)}$

f_0——太阳能保证率，取 0.6

η_{cd}——集热器集热效率，取 0.5

η_c——管路及储热水箱热损失率，取 0.2

计算得 $A_c=4.16\ \mathrm{m^2}$。

1.2.3 抛物面设计

阳光经过聚光集热器光孔（即抛物面的开口宽度，图 4 中为宽度 b）进入聚光器，其大小决定聚光器的输入总能量。聚光度与集热器效率呈正相关[18]。对于圆管型接收器，相对光孔 $n=4$ 时，聚光比 $K=68.4$ 为最大值。确定光孔宽度 $b=2.4$ m。焦距 $f=b/n=0.6$ m，集热器最小直径为

$$d_{\min}=2\left(f+\frac{1}{4f}\frac{b^2}{2}\right)\sin\frac{D}{2} \tag{12}$$

式中 D——太阳径角，取 0.53°

故 $d_{\min}=0.0168$ m。

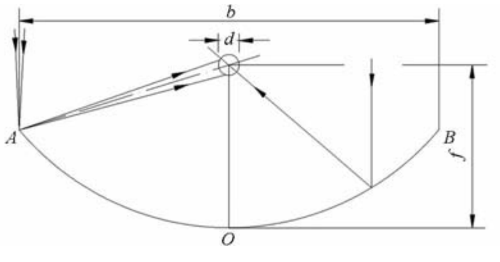

图 4 抛物面聚光器聚光效能

Fig. 4 Concentration efficiency of PTC

1.2.4　集热器角度设计

当太阳光与抛物面开口口径垂直时，抛物反射面所接收到的直射阳光最多，聚光器最佳倾角为

$$b_1 = \tau - \delta_1 \tag{13}$$

式中　τ——当地纬度，杨凌地区纬度 N34°16′

b_1——聚光型集热器最佳倾角

δ_1——赤纬角

通过计算，得出 2012—2014 年的太阳赤纬角的月平均值（图 5）。

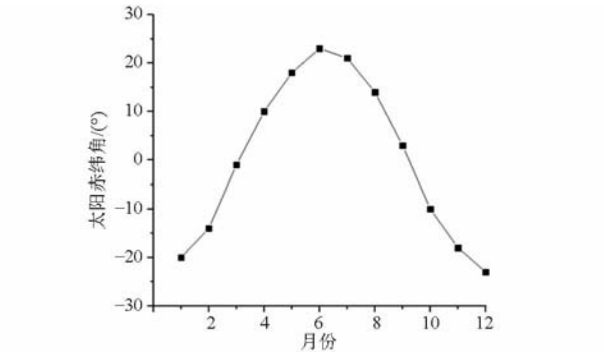

图 5　最近 3 年月平均太阳赤纬角统计结果

Fig. 5　Statistic result of average solar declination in recent three years

由式（13）可得出集热器在一年间的倾角变化如图 6 所示。

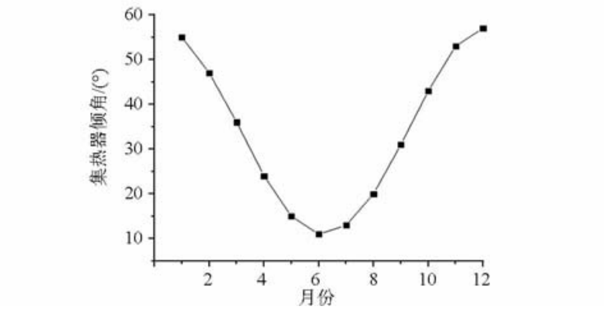

图 6　一年中集热器倾角变化曲线

Fig. 6　Changing curves of heat collector angle

1.2.5　倾角及支架

在倾角控制设计方面，手柄连杆纵向开槽，定位板横向打孔，当手柄转过一定角度且需要固定时，手柄和定位板通过槽和铰制孔螺栓连接，选择 GB27—88 系列六角头螺栓，利用螺栓的抗剪能力与摩擦力对手柄及旋转抛物镜面定位。图 7 中手柄的位置是 2 个极限位置，分别代表 12 月份及 6 月份的支架倾角，1—5月及 7—11 月的支架倾角在这两者之间。

2　系统传热仿真与试验验证

采用 Fluent 和 Gambit 软件对聚光集热器供热厌氧反应系统进行传热仿真，以确定和验证系统设计的合理性。

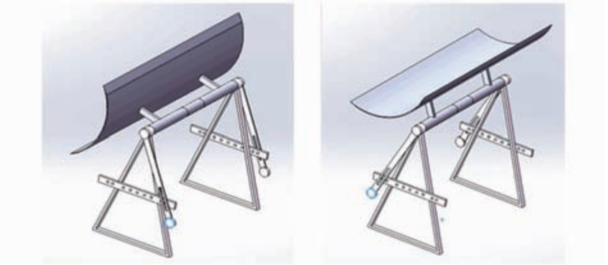

图 7　集热器模型

Fig. 7　Model of PTC

2.1　模型构建

设反应器进口水温为 75℃，并假设：①反应器上 1/4 处为气体部分。②气液交界面的散热效果与壁面相同。③忽略料液发酵产热和产气带走的热量。④默认进口温度恒定[19]。由此建立的反应器模型如图 8 所示。由于管径几何尺寸与反应器整体几何尺寸相差很大，因此有必要对料液进行分区，进而简化网格。将其分为近管料液区和远管料液区，在 Gambit 中设置交界面 interface，并在 Fluent 中确认。

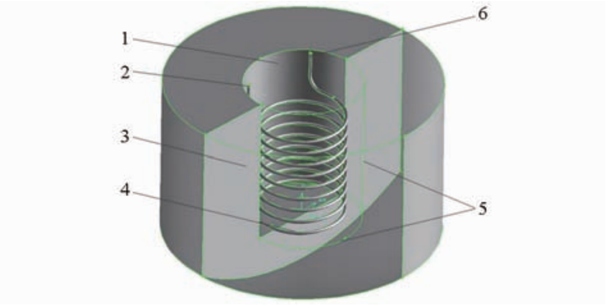

图 8　反应器几何模型

Fig. 8　Geometrical model of reactor

1. 近管料液区　2. 热水进口　3. 远管料液区　4. 加热管　5. 交界面　6. 热水出口

2.2　网格划分

由于四面体网格具有适应较复杂几何结构的优势，故选择 Tgrid 四面体网格划分模型[20]，根据不同尺寸，确定换热管部分单位网格尺寸为 7，网格数为 298 464，近管料液区单位网格尺寸为 20，网格数为 1 672 622，远管料液区的网格尺寸为 40，网格数为 894 413，模型 3 部分网格如图 9 所示。

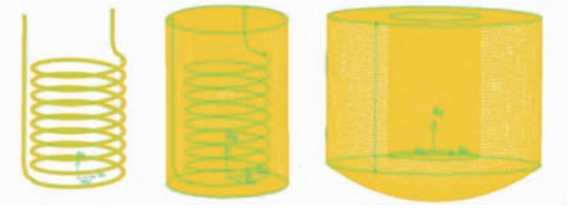

图 9　模型网格图

Fig. 9　Grid of model

2.3　仿真结果

已知集热器真空管的直径为 0.016 8 m，反应器

中换热管内径为 0.03 m。为保证陕西省杨凌地区厌氧反应器料液在 35℃左右条件下全年运行，至少有 7 个月需要外界提供热源，且换热管进口温度不低于 50℃。进口流量设定为 150 L/h，换算为进口流速约为 0.06 m/s。通过系统优化设计，保证进入反应器时工质温度为 50℃以上。通过能量平衡计算，在考虑进料损失和装置散热损失的基础上，得出反应器壁面热损失为 22.5 W/m^2，设置散热形式为 Heat Flux。

通过仿真计算，得到稳态条件下换热管对反应器的换热效果。由图 10 可见，在设定工况下，螺旋形换热器中的工质从聚光集热器中获得能量，对反应器内料液具有良好的加热效果，料液温度基本维持在 35℃左右。

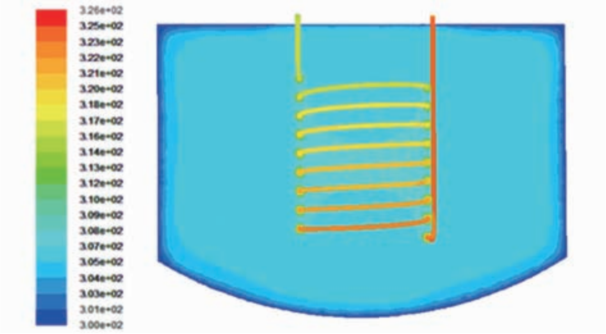

图 10　厌氧反应器 PTC 加热仿真效果

Fig. 10　Simulation result of PTC heating anaerobic reactor

2.4　试验验证

2015 年 11 月 25 日在陕西省杨凌示范区崔西沟户用沼气池进行试验验证。试验装置包括：4.2 m^2槽式太阳能集热器、0.25 m^3储热水箱、8 m^3地下厌氧反应器、循环水泵、加热盘管和温度传感器（图 11）。5 d 后沼气池料液温度趋于稳定，11 月 30 日试验结果见图 12，室外最低环境温度为 0.1℃，室外最高环境温度为 11.2℃，储热水箱内太阳能热水最低温度为 37.2℃，最高温度为 78.4℃，厌氧反应器内料液最低温度为 33.6℃，最高温度为 35.8℃。试验证明，采用与设计参数相近的 PTC 系统为 8 m^3地下厌氧反应器提供热源，可使厌氧反应器内料液温度保持在（34.7 ± 1.1）℃，与 Fluent 仿真结果基本吻合。

图 11　PTC 供热厌氧反应器实物图

Fig. 11　Photo of PTC heating anaerobic digester

1. 地下厌氧发酵系统　2. 聚光集热器　3. 储热水箱

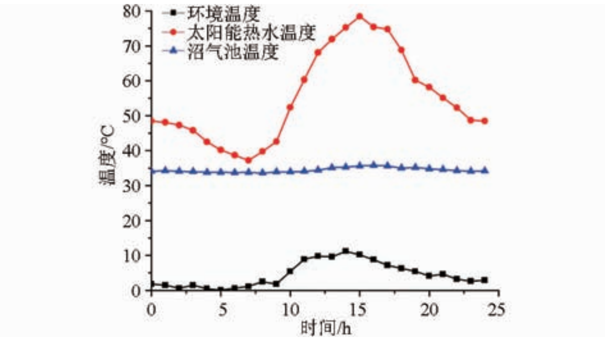

图 12　太阳能热水温度、环境温度和沼气池温度变化规律

Fig. 12　Variations of water temperature, environment temperature and biogas digester temperature

3　结论

（1）进料热损失与发酵物料散失热量为反应器最主要的负荷，PTC 加热的厌氧反应器系统二者分别为16 077.31 kJ/d和 23 180.01 kJ/d。

（2）PTC 加热厌氧反应器中的 PTC 光孔宽度 b 为 2.4 m、焦距 f 为 0.6 m、集热管直径为 0.016 8 m 时，能够获得最大的集热能量。

（3）通过初步的计算机仿真和试验验证，证明 PTC 对厌氧反应器内物料具有良好的加热效果，能够保持反应器内部料液温度在 35℃左右。

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