The effect of biogas fermentation assisted by simple solar greenhouse

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Abstract. Biogas fermentation rate is largely affected by environment temperature, causing a much more difficult production of biogas digesters in cold winter, for most regions in China. Combining the abundant solar energy resources and biomass dry anaerobic fermentation together, solar thermal energy can guarantee the production of biogas in winter. With this method, the prediction of the appropriate fermentation temperature is required. In this study, the effect of temperature on biogas fermentation was studied. To predict the fermentation temperature, a heat transfer model of biogas fermentation based on a project in city Xuzhou, which assisted with a simple solar greenhouse, was established according to the heat transfer theory. The maximum difference between the measured and calculated fermentation temperature was 2%. The effect of biogas fermentation assisted by simple solar greenhouse in typical city of different climate zones, including severe cold region, cold region and hot summer and cold winter region, was studied with the combination of heat transfer model and temperature-based biogas production rates prediction model. The results showed that, the gas production rate of biogas fermentation increases with the increase of temperature in a certain range. Assisted by simple solar greenhouse, the biogas digester temperature is increased by 6~8℃ compared with the previous one, ensuring a better daily gas production rate of 0.5~0.7m^3/m^3 in winter.

Nomenclature

$H_{t(\theta)}$ solar radiation on the tilted surface (W/m^2)
H total radiation on the horizontal surface (W/m^2)
R ratio of the total radiation on the tilted surface and the horizontal surface
H_b average daily amount of horizontal direct radiation per month (J/ (m^2. d))
H_d average daily amount of horizontal scattered radiation per month (J/ (m^2. d))
ρ ground reflection coefficient
α roof angle
R_b ratio of the direct solar radiation on the tilted surface and the horizontal surface
φ local latitude
δ declination angle of the sun
ω_0 sunrise and sunset hour angle on the south tilted surface
θ angle between the direction to the sun and the normal to the surface
n serial number of the calculating day in a year
Q_r solar radiation energy collected by the greenhouse (W)
F_r actual daylighting area
τ_g transmittance of the daylighting surface
T_z solar-air temperature (℃)
T_{air} outdoor air temperature (℃)
a solar absorption rate on envelop external surface
I solar radiation
α_{out} convective heat transfer coefficient of envelop external surface
Q_{lw} long wave radiation of the envelop external surface with the sky and the surrounding objects (W)

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https://doi.org/10.1051/e3sconf/202124603001

Q_d heat transfer between indoor air and the ground (W)
k_d heat transfer coefficient of the ground (W/(m^2·K))
F_d ground area (m^2)
T_a air temperature in the greenhouse (℃)
T_d ground temperature (℃)
Q_h heat transfer between indoor air and the back slope (W)
k_h heat transfer coefficient of the back slope (W/(m^2·K))
F_h back slope area (m^2)
Q_{wi} heat transfer between indoor air and outdoor air through external walls (W)
α_T temperature correction factor
k_{wi} heat transfer coefficient of the wall (W/(m^2·K))
F_{wi} wall area (m^2)
T_{zi} solar-air temperature, where i stands for orientation, 1 ~ 4, respectively representing east, west, south and north (℃)
Q_m heat transfer between indoor air and outdoor through the film (W)
k_m heat transfer coefficient of the film (W/(m^2·K))
F_m film area (m^2)
K heat transfer coefficient (W/(m^2·K))
α_1 convective heat transfer coefficient of the inner surface (W/(m^2·K))
α_2 convective heat transfer coefficient of the outer surface (W/(m^2·K))
δ_i thickness of layer i (m)
λ_i thermal conductivity of the i-layer material (W/ (m· K))
Q_l heat transfer between the indoor air and the biogas digester (W)
F_1 lateral surface area of the biogas digester (m^2)
F_2 top surface area of the biogas digester
T_l fermentation temperature (℃)
k_1 heat transfer coefficient of cylindrical lateral surface (W/(m^2·K))
k_2 heat transfer coefficient of cylindrical top surface (W/(m^2·K))
d_1 tube diameter (m)
d_2 outer diameter of the tube (m)
λ thermal conductivity of the biogas digester (W/ (m· K))
ρ_a indoor air density (kg/m^3)
V_a total volume of indoor air (m^3)
C_a specific heat capacity of indoor air (J/ (kg. K))
τ time (s)
r_r proportion of solar radiation absorbed by the air in the greenhouse
ρ_l density of water (kg/m^3)
V_l volume of the fermentation liquid (m^3)
C_l specific heat capacity of water (J/ (kg. K))
$\dot{v}_j$ volume flow rate of the input material (m^3/s)
T_j temperature of the input material (℃)

1 Introduction

In the process of biomass anaerobic fermentation, if fermentation temperature is too low or the temperature fluctuates too fast, the gas production efficiency and the content of methane in the biogas produced will be reduced [1]. In most areas of China, the winter is cold for a long time, and the biogas production rate and decomposition rate of raw materials are low. Therefore, it is necessary to adopt economical and efficient heat preservation and warming measures for biogas fermentation.

The warming measures for biogas digester mainly include electric heating method, coal boiler heating method, pool heating method, biomass boiler heating method, "pigs a bog a kang" warming method, solar greenhouse warming technology, biogas generator waste heat technology, ground source heat pump (GSHP) heating technology, active solar energy heating technology, hybrid solar heating technology and combined warming technology, etc. Electric heating method consumes electric energy, and the economic cost is also higher. The thermal energy conversion rate of coal boiler heating method, pool heating method, biomass boiler heating method and "pigs a bog a kang" warming method is low, and the combustion of fuel causes air pollution [2]. The biogas generator waste heat technology uses the heat generated by the biogas engine cooling system and the exhaust heat to increase the temperature of the biogas digester, which can increase the biogas production rate by about 4 times [3]. The technology relies on biogas power generation projects and is not universally applicable. GSHP heating technology can provide a stable but low temperature heat source from the soil, which is suitable for medium-temperature fermentation and has the advantages of high efficiency, energy saving and environmental protection. The disadvantages are that this technology requires the digging of buried wells and laying of buried pipes, resulting in relatively high cost and technical requirements. Moreover, it is not suitable for the high-temperature fermentation system that needs heating all the year round, and will be limited by the geological water quality in different regions [4]. In addition, in order to warm biogas digester, the heat is extracted from soil in winter, but no heat is released to soil in summer. As a result, the heat taken (discharged) from soil is unbalanced in winter and summer, which affects the long-term stable operation of the GSHP system [5].

https://doi.org/10.1051/e3sconf/202124603001

Combined warming technology refers to the combination of various heating modes, such as solar energy combined coal-fired boiler model, solar energy combined biogas boiler model[6], generation waste heat combined biogas boiler model, solar energy combined GSHP model [7], etc.

Among them, the technologies of using solar assisted biogas thermal insulation are mainly passive solar greenhouse warming technology, active solar heating technology and hybrid solar heating technology. Alvarezr et al. [8] established an organic waste treatment and utilization system integrating a flat-plate solar collector, an anaerobic fermentation device and an artificial wetland, with a fermentation temperature of the system up to 46℃. Zhong et al. [9] designed a solar heating system in Michigan, USA. The system consists of an all-glass solar vacuum tube heat collector, heat exchanger, and anaerobic fermentation unit, which raises the fermentation temperature from 20℃ to 35℃. In order to heat the water jacket around the biogas digester, Alkhamis et al. [10] designed, manufactured and installed an all-glass solar vacuum tube heat collector and heat exchanger, so that the water jacket can be kept at a constant temperature of 40℃. Hassanein et al. [11] designed a hybrid solar heating system consisting of a greenhouse of 120 m^3 and a heat tube solar collector with a total surface area of 20 m^3, which was assisted the use of electric heating. In winter, the solar system can produce an additional 12 m^3 of biogas per day from the biogas fermentation unit. The application of active solar heating technology and hybrid solar heating technology to large biogas projects results in high costs.

Passive solar greenhouse heating technology is the use of solar greenhouse for the overall heating of the biogas pool, and the greenhouse is easy to build and the cost of construction, operation and maintenance is low. As early as 1985, Bansal et al. [11] constructed a gridded solar greenhouse in New Delhi, India, which could raise the ambient temperature of the biogas digester from 18℃ to about 37℃, the best temperature for anaerobic fermentation, and increase the gas production by 15% ~ 20%. Kumar et al. [12]studied the influence of plastic as insulation material instead of brick and stone material on biogas digester in a solar greenhouse near Nilgiris, India. Compared with the traditional biogas digester, the indoor temperature and gas production of the biogas digester are 22.4℃ and 34.6 kg /d, the average annual temperature of the experimental biogas digester can reach 26.3℃ and the gas production is 39.1 kg /d. The research results of Hu Guohua et al. [13] showed that the temperature of the anaerobic reactor using the new solar greenhouse was 7.6~13.5℃ higher than that of the traditional anaerobic reactor. Based on the solar greenhouse, the increase of temperature and the stability of temperature change can increase the output of biogas and ensure the stability of gas production.

At present, the main heat preservation measures of biogas digester include digging ring trench, covering the surface of biogas digester with firewood, heat preservation materials, solar greenhouse, burying the whole biogas fermentation system underground and so on. It can be seen that solar greenhouse is also an effective insulation technology.

In this study, the effect of temperature on biogas fermentation assisted by solar greenhouse was studied. To predict the fermentation temperature, a heat transfer model of biogas fermentation based on a project in city Xuzhou, which assisted with a simple solar greenhouse, was established according to the heat transfer theory.

2 Heat transfer model

2.1 Project background

In this paper, the straw biogas project in a village in Xuzhou is taken as the object to study the thermal insulation and temperature increasing effects of biogas digester under different weather conditions in summer and winter of solar greenhouse. As can be seen from **Fig. 1**, solar greenhouse warming technology can be used to warm biogas digester in Xuzhou due to relatively high solar radiation. The heat transfer model based on the experimental data of Xuzhou and the meteorological data of other places can also be used to analyze the effect of biogas fermentation in this area.

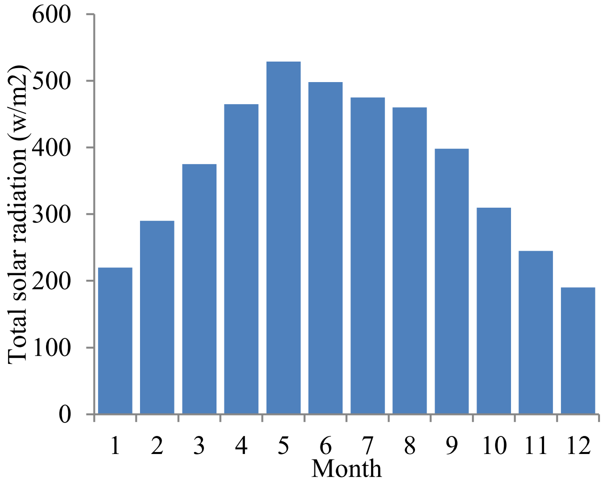

Fig. 1 The monthly total solar radiation in Xuzhou

Fig. 2 shows the geometric model and heat transfer schematic diagram of biogas fermentation system assisted by simple solar greenhouse. The heat transfer process in the solar greenhouse is composed of the following processes: (1) solar radiation enters the greenhouse through the daylighting film and the envelop, and transfers heat with indoor surfaces; (2) the heat is exchanged between the air inside the greenhouse and the outside through the envelop and film; (3) biogas digester exchanges heat with air and soil.

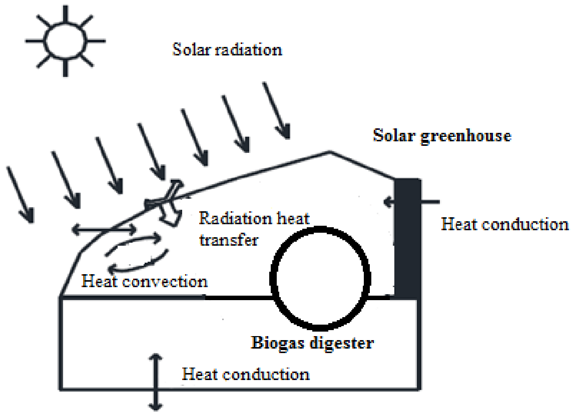

Fig. 2 Schematic of heat transfer in a solar greenhouse

2.2 Heat transfer process

2.2.1 Lighting surface solar radiation

The lighting surface of the greenhouse is simplified to the tilted surface as shown in **Fig. 3**. General meteorological stations provide the data of solar radiation on the horizontal surface, so it is necessary to calculate solar radiation on the tilted surface. The Klein [14] method is widely used to calculate solar radiation on the tilted surface.

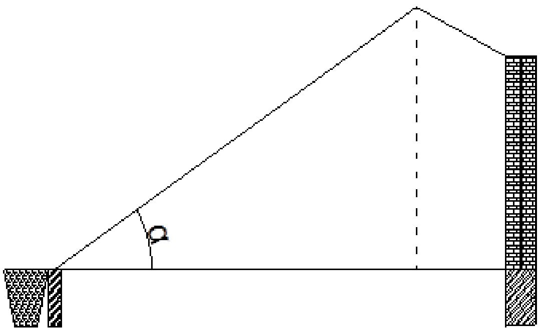

Fig. 3 Greenhouse equivalent lighting surface

The calculation formula of solar radiation $H_{t(\theta)}$ on the tilted surface is as follows:

$$H_{t(\theta)} = H \cdot R \tag{1}$$

Where R is calculated according to equation (2) [15] below.

$$R = \frac{H_b}{H} \cdot R_b + \frac{H_d}{H} \cdot \frac{(1+\cos\alpha)}{2} + \frac{\rho(1-\cos\alpha)}{2} \tag{2}$$

Generally take ρ = 0.2. R_b is calculated according to equation (3) [16-18] below.

$$R_b = \frac{\cos(\varphi-\alpha)\cos\delta\sin\omega_0 + \dfrac{\pi}{180}\omega_0\sin(\varphi-\alpha)\sin\delta}{\cos\varphi\cos\delta\sin\omega_0 + \dfrac{\pi}{180}\omega_0\sin\varphi\sin\delta} \tag{3}$$

ω_0 can be calculated from the following equation (4) [17].

$$\omega_0 = \cos^{-1}(-tg(\varphi-\theta)tg\delta) \tag{4}$$

Year-round declination varies from +23.45° to -23.45°, which can be calculated by the following simplified equation (5) [19].

$$\delta = 23.45 \times \sin(360 \times \frac{284+n}{365}) \tag{5}$$

The solar radiation energy collected by the greenhouse can be calculated by equation (6) below.

$$Q_r = H_{t(\theta)} \times \mathrm{F_r} \times \tau_{\mathrm{g}} \tag{6}$$

The lighting surface of the greenhouse was made of single-layer PVC film. Considering the actual use of aging and other factors, the paper take τ_g =0.7.

For example in Xuzhou, φ is 34.28 °and α is set as 32 ° in the project, which conforms to formula $\alpha \geq \delta$ - φ -35 °. The monthly mean values of horizontal direct radiation and scattered radiation are shown in **Table 1**, and the values of monthly R are obtained from the above formula.

Table 1 Ratio of total tilted radiation to total horizontal radiation in every month in Xuzhou

Month	H_d (MJ/(m^2.d))	H_b (MJ/(m^2.d))	R
January	5.45	1.63	1.18
February	6.84	3.31	1.16
March	8.03	3.59	1.04
April	8.67	6.83	0.99
May	6.57	10.51	0.93
June	9.56	6.98	0.91
July	10.55	4.75	0.92
August	10.48	4.26	0.95
September	8.01	5.36	1.04
October	6.13	4.16	1.16
November	4.32	3.87	1.39
December	4.12	2.19	1.36

2.2.2 Solar radiation passing through the opaque envelop

The heat transfer of solar radiation through the wall is calculated by the integrated temperature method. In engineering, the enhancement effect of solar radiation to outdoor air temperature (T_{air}) on the envelop is measured by an imaginary temperature, which is called the solar-air temperature (T_z). The equation is as follows.

$$T_z = T_{air} + \frac{aI}{\alpha_{out}} - \frac{Q_{lw}}{\alpha_{out}} \tag{7}$$

The above formula not only considers the short-wave radiation from the sun to the envelop, but also reflects the long-wave radiation between the envelop external surface and the sky and surrounding objects. In some cases, the long-wave radiation can be ignored, and the above equation can be simplified as following equation (8).

$$T_z = T_{air} + \frac{aI}{\alpha_{out}} \tag{8}$$

There is no effect of solar radiation at night, and the background temperature of the sky is far lower than the air temperature. Therefore, the heat transferring from the buildings to the sky cannot be ignored, especially in the case of relatively large angle coefficient between the buildings and the sky. Since the long wave radiation of the environmental surface depends on the angle coefficient, which is related to the shape, distance and angle of the environmental surface, it is difficult to obtain, and empirical values are often used. One method is to approximate Q_{lw} = 0 for the vertical surface and (Q_{lw}/α_{out}) =3.5 ~ 4.0℃ for the horizontal surface.

2.2.3 Heat transfer of the envelop

The heat transfer between the greenhouse and the external environment of the enclosure structure includes the heat transfer from the external wall, the back slope, the daylighting surface and the soil.

$$Q_d = k_d F_d (T_a - T_d) \tag{9}$$

The heat transfer coefficient of indoor ground varies with the distance from the outer wall, and the heat transfer on the ground above 8m from the outer wall is basically unchanged. Therefore, the parallel direction of the ground exterior wall can be divided into four calculation zones by using approximate method, as shown in **Fig. 4** below.

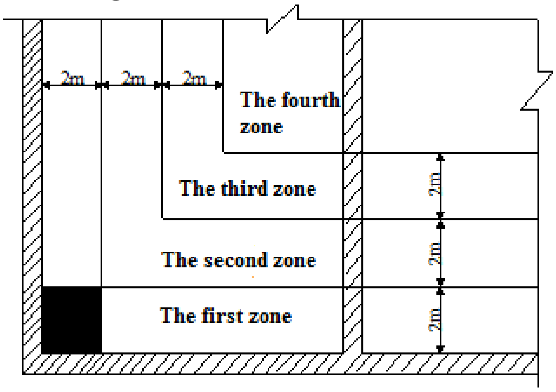

Fig. 4 Subdivision of ground heat transfer zone

$$Q_h = k_h F_h (T_a - T_z) \tag{10}$$

Q_h is the heat transfer between indoor air and the back slope.

$$Q_{wi} = \alpha_T k_{wi} F_{wi} (T_a - T_{zi}) \tag{11}$$

Q_{wi} is the heat transfer between indoor air and outdoor air through external walls.

$$Q_m = k_m F_m (T_a - T_{air}) \tag{12}$$

Here Q_m the heat transfer between indoor air and outdoor through the film.

The calculation formula of heat transfer coefficient (K) of homogeneous multi-layer flat wall, such as wall and back slope, is as follows.

$$K = \frac{1}{\frac{1}{\alpha_1} + \sum_{i=1}^{m} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}} \tag{13}$$

2.2.4 Heat exchange between the air in the greenhouse and the biogas digester

The physical model of the biogas digester is shown in **Fig. 5** below. The biogas digester is approximately a cylinder with most of its outer surface exposed to the air inside the greenhouse and a small part buried in the soil. The material of the biogas digester is steel plate. In order to make full use of solar radiation, the outer surface of the biogas digester is coated with black solar energy selective absorption coating with an absorption rate of 95% [20].

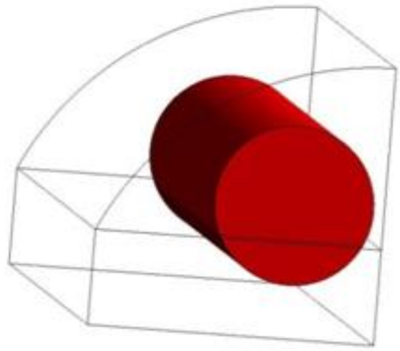

Fig. 5 Physical model of the biogas digester

$$Q_l = k_l F_l (T_a - T_l) \tag{14}$$

$$k_l F_l = k_1 F_1 + 2 k_2 F_2 \tag{15}$$

Here Q_l is the heat transfer between the indoor air and the biogas digester.

The heat transfer coefficient (k_1) calculation formula of cylindrical lateral surface is as follows.

$$k_1 = \frac{1}{\frac{d_2}{\alpha_1 d_1} + \frac{1}{2\lambda} In \frac{d_2}{d_1} + \frac{1}{\alpha_2}} \tag{16}$$

When the indoor air velocity ($V_{f,a}$) is small, the heat transfer is mainly natural convection. The convection heat transfer coefficient of indoor air to the outer surface of the biogas digester can be approximately calculated according to the following equation [21].

$$\alpha_2 = 4, V_{f,a} \le 0.50 \tag{17}$$

2.3 Thermal equilibrium equations

Because the heat transfer inside the greenhouse is more complex, this paper puts forward the following hypothesis to simplify the internal heat transfer.

- The variation of air density, pressure, specific heat capacity and water vapor content inside the greenhouse is small, which is quoted as constant value.
- The ground, wall and film are regarded as isotropic and equivalent to the greybody.
- Since the intensity of solar radiation is much greater than that of long-wave radiation, the long-wave radiation heat transfer in the surface of the envelop facing the sky and surrounding objects during the day is ignored.

- Because the solar greenhouse is closed, the influence of ventilation penetration is ignored.
- The physical parameters of soil are regarded as constant.
- The greenhouse wall and soil have little heat storage capacity, so the heat storage capacity of wall and soil is ignored.

Therefore, the heat balance and heat transfer model is suitable for greenhouse without ventilation. At the same time, many parameters with small changes are assumed as constants, simplifying the calculation of the equations, and the error of the results is acceptable.

The dynamic thermal balance equation of the air in the greenhouse is shown below.

$$\rho_a V_a C_a \frac{dT_a}{d\tau} = r_r Q_r + Q_d + Q_h + \sum_{i=1}^{3} Q_{wi} + Q_m + Q_l \quad (18)$$

Combine the above equations to get the following equation.

$$\rho_a V_a C_a \frac{dTa}{d\tau} = r_r H_{t(\theta)} RF_r \tau_g - k_d F_d \left(T_a - T_d\right) - k_h F_h (T_a - T_{zh})$$
$$-\sum k_{wi} F_{wi} (T_a - T_{zi}) - k_m F_m (T_a - T_{zm}) - k_l F_l (T_a - T_l) \quad (19)$$

As the semi-buried biogas digester belongs to fluid-pipe-soil coupled heat transfer, which is relatively complex, there are few references on heat dissipation of semi-buried pipeline at present, and the linear interpolation model is not accurate. The heat transfer from the biogas digester to the soil is far less than that from the air. To simplify the calculation, the heat transfer from the biogas digester to the soil is ignored. In order to obtain the heat balance equation, the heat transfer inside the biogas digester is simplified as follows.

- Due to less dry matter in fermentation, biogas fermentation liquid is regarded as water, whose density, pressure and specific heat capacity are regarded as constant values, and the temperature of fermentation liquid is uniform.
- The long wave radiation heat transfer between the inner surface of envelope and the outer surface of the biogas digester is ignored.
- During the whole fermentation process, the materials are continuously put in and discharged at the same time.
- Heat transfer from the biogas digester to the soil is ignored.
- The heat storage capacity of the biogas digester is ignored.
- The heat taken away by the biogas is ignored.
- Heat generation in biological fermentation is ignored.

Compared with the fermenting liquid temperature, the input material temperature is relatively low. In this paper, it is assumed that the temperature of input material is constant at 10℃. Therefore, the solar radiation of the biogas digester and the heat transfer with the air in the greenhouse are also used to heat the input material. According to the dynamic thermal balance, the following equation can be obtained.

$$\rho_l V_l C_l \frac{dT_l}{d\tau} + \rho_l \dot{v}_j C_l (T_l - T_j) = (1 - r_r) Q_r + Q_l$$

$$\rho_l V_l C_l \frac{dT_l}{d\tau} + \rho_l \dot{v}_j C_l \left(T_l - T_j\right) = \left(1 - r_r\right) H_{t(\theta)} RF_r \tau_g + k_l F_l \left(T_a - T_l\right) \quad (20)$$

By combining equations (19) and (20), the typical annual meteorological data [22] dedicated to the analysis of the thermal environment of Buildings in China are taken, and the annual air temperature of greenhouse and the temperature of the fermentation liquid can be obtained by setting the initial value.

2.4 Experimental verification of the model

Fig. 6 shows the comparison of fermentation liquid temperature measured and calculated in May 21and January 12. The fermentation temperature can be maintained at about 18.5℃ in the middle of January, the coldest period in winter, and about 33-34 ℃ in the middle of May. The difference between the measured and calculated values is -2% in winter and 1% in summer, and the error is very small.

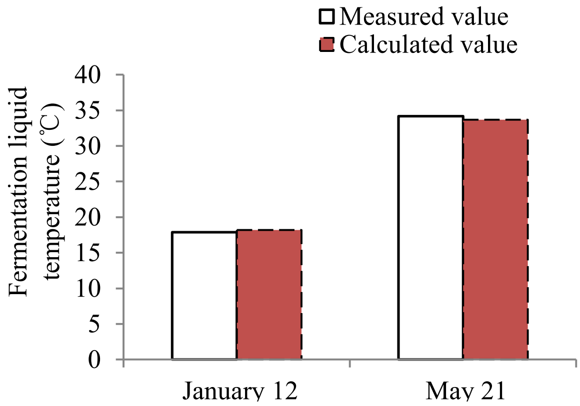

Fig. 6 Comparison of fermentation liquid temperature measured and calculated in May 21 and January 12.

2.5 Effect of fermentation temperature on gas production rate

Based on existing studies [23-25], the influence of temperature on gas production rate is shown in **Fig.7** below. According to the temperature of fermentation liquid obtained above, the gas production rate of biogas can be obtained daily.

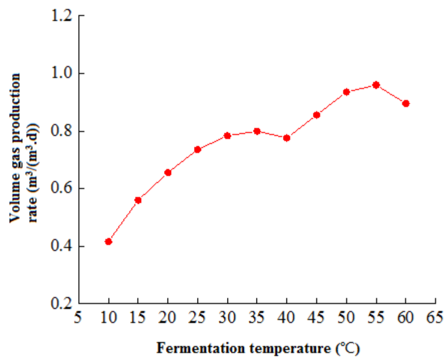

Fig. 7 Gas production rate model at different fermentation temperatures

3 Results and discussion

Fig. 8 shows the monthly average outdoor air temperature, indoor air temperature, fermentation temperature and gas output in a year. It can be seen that the temperature inside the greenhouse and the fermentation temperature are positively correlated with the outdoor air temperature. The average temperature inside the greenhouse is about 12℃ higher than the outdoor air temperature. The fermentation temperature is generally 3 ~ 5℃ higher than the temperature inside the greenhouse, and there is a certain temperature wave delay compared with the temperature inside the greenhouse. In January, the coldest month, the average temperature of fermentable liquid was 17.0℃, and in August, the hottest month, it reached 40.7℃. The maximum, minimum and average daily fermentation temperature of the whole year were 41.4℃, 15.4℃ and 29.5℃ respectively. Due to the large specific heat capacity of the fermentation liquid, the temperature variation of the fermentation liquid within one day is small. The gas production is lowest in January, higher in May and October, and lower from June to September, because the gas production rate drops when the fermentation temperature is around 40℃ compared to 35℃. During the period, the greenhouse can be ventilated and cooled to improve the gas production rate.

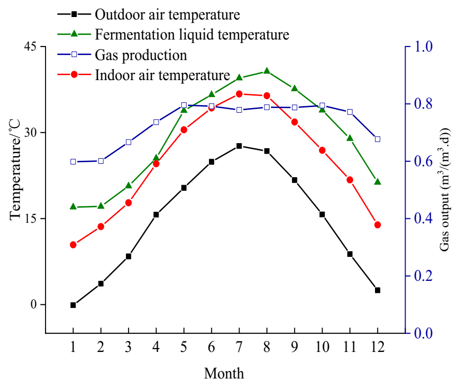

Fig. 8 The temperature and gas output of the solar greenhouse methane project in Xuzhou

Fig. 9 compares the fermentation temperature of the solar biogas digester in Xuzhou with that in traditional biogas digesters in Chengdu, Changsha and Hangzhou [1]. It can be seen that the biogas digester assisted by simple solar greenhouse has a good warming effect. In the past, the temperature of the underground biogas digester can reach up to 26℃ in summer, and the maximum temperature of the solar biogas digester can reach 40℃. In winter, the temperature of the solar biogas digester is about 6 ~ 8℃ higher than that of the traditional digester, which ensures a better gas production rate and the average daily gas output can reach 0.5 ~ 0.7$m^3(m^3.d)$.

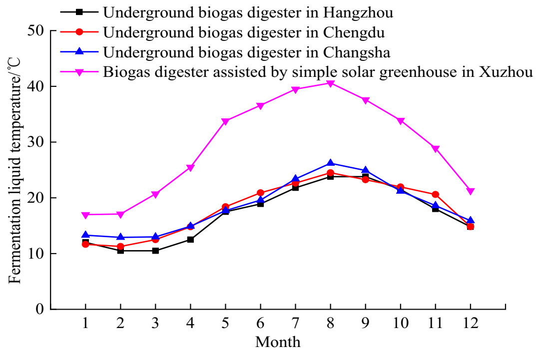

Fig. 9 The fermentation temperature of the solar biogas digester in Xuzhou with that in traditional biogas digesters in Chengdu, Changsha and Hangzhou

By using the above heat transfer model, the temperature and gas output of the solar greenhouse methane project in Jinan, Lhasa, Harbin, Shanghai, Ningde and Chengdu are shown in **Fig. 10** to **Fig.15**.

Jinan, Lhasa and Xuzhou are in the cold region, but Lhasa is abundant in solar energy resources. The annual gas output of Jinan and Xuzhou is similar. The average monthly gas output of Jinan is over 0.6 $m^3(m^3.\ d)$, as shown in **Fig. 10**. The solar energy resources in Lhasa are abundant all year round, so the fermentation temperature fluctuates slightly and is around 30℃ ~ 40℃ all year round. The annual average monthly gas production in Lhasa is around 0.8 $m^3(m^3.\ d)$, which is very suitable for residents with stable supply of gas, as shown in **Fig. 11**.

Harbin is in the severe cold region. The average temperature in January is around -18 ℃, the average monthly fermentation temperature is around 10℃, and almost no gas is produced below 10℃. Meanwhile, the fermentation temperature in February is below 10℃, so Harbin cannot produce gas continuously in January and February, as shown in **Fig. 12**.

Shanghai, Ningde and Chengdu are in hot-summer and cold-winter region. The annual fermentation temperature in Shanghai is above 15℃, and the gas output is above 0.6 $m^3(m^3.d)$, as shown in **Fig. 13**. The outdoor air temperature in Ningde is relatively high, and the solar radiation in September and October in autumn is higher than that in other months. Therefore, the fermentation temperature reaches the highest in September, reaching 45℃, and the gas production rate can reach more than 1.0 $m^3(m^3.d)$, as shown in **Fig. 14**. Chengdu has poor solar energy resources, resulting in low fermentation temperature, the highest fermentation temperature is 37℃, and the gas production rate is above 0.5 $m^3(m^3.d)$, as shown in **Fig. 15**.

It can be seen that the gas production rate in summer is similar in all regions. The total annual gas output is the highest in Lhasa, followed by Ningde, Jinan, Shanghai and Chengdu, and the lowest is in Harbin. The total annual biogas production capacity is about 287m^3 in Lhasa, 285m^3 in Ningde, 276m^3 in Jinan, 274m^3 in Shanghai, and 262m^3 in Chengdu, and only 229m^3 in Harbin due to a period of no gas production. In summer,

https://doi.org/10.1051/e3sconf/202124603001

there will be excess production of biogas in Harbin. In order to optimize the production and utilization of biogas, dry grain storage and other industries can be considered. Because the equipment needed for long-term storage of biogas is relatively expensive and there are safety risks, it is more feasible to adjust the feeding amount and time. For users with continuous gas demand, it is not suitable to promote this technology in Harbin.

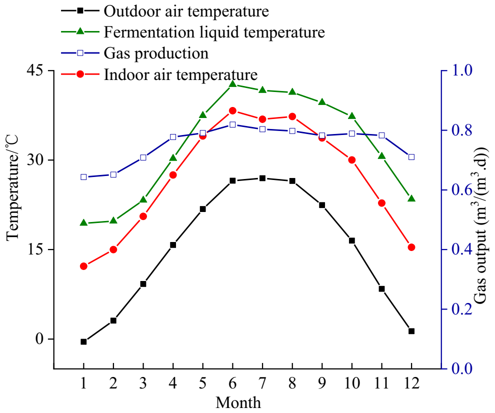

Fig.10 The temperature and gas output of the solar greenhouse methane project in Jinan

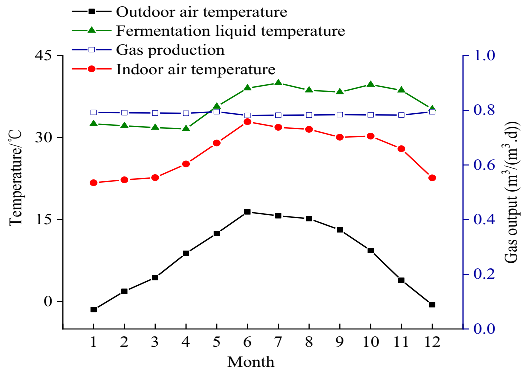

Fig.11 The temperature and gas output of the solar greenhouse methane project in Lhasa

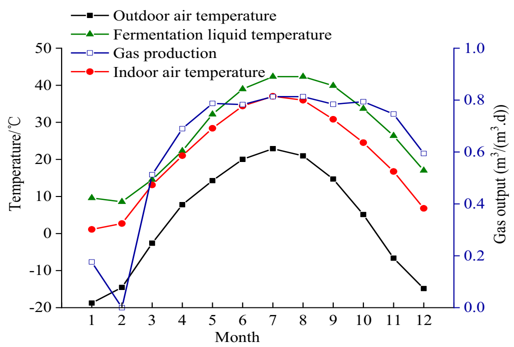

Fig.12 The temperature and gas output of the solar greenhouse methane project in Harbin

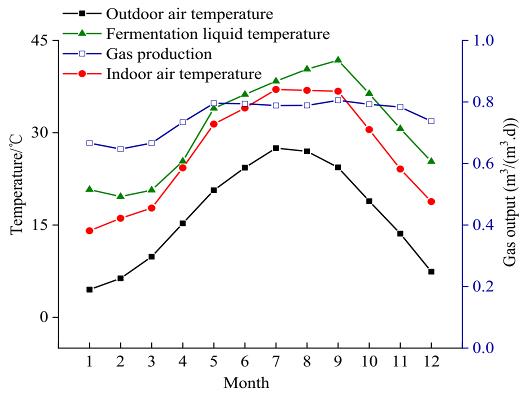

Fig.13 The temperature and gas output of the solar greenhouse methane project in Shanghai

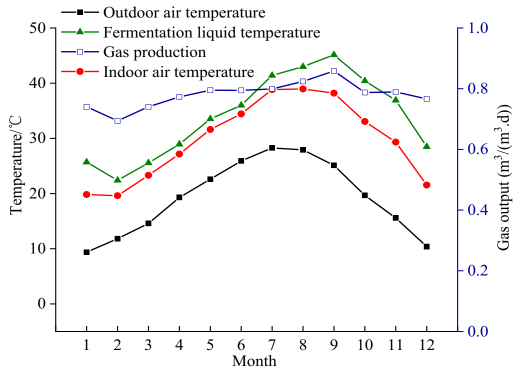

Fig.14 The temperature and gas output of the solar greenhouse methane project in Ningde

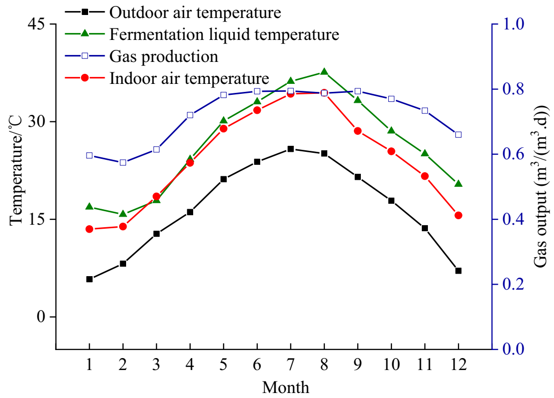

Fig.15 The temperature and gas output of the solar greenhouse methane project in Chengdu

4 Conclusion

In this study, the effect of temperature on biogas fermentation was studied. To predict the fermentation temperature, a heat transfer model of biogas fermentation based on a project in city Xuzhou, which assisted with a simple solar greenhouse, was established according to the heat transfer theory. The maximum difference between the measured and calculated fermentation temperature was 2%. The results showed that, the gas production rate of biogas fermentation increases with the increase of temperature in a certain range. Assisted by simple solar greenhouse, the biogas digester temperature is increased by 6~8℃ compared with the previous one, ensuring a better daily gas production rate of 0.5~0.7m^3/m^3 in winter.

The effect of biogas fermentation assisted by simple solar greenhouse in typical city of different climate zones, including severe cold region, cold region and hot summer and cold winter region, was studied with the combination of heat transfer model and temperature-based biogas production rates prediction model. The average monthly temperature, fermentation temperature and daily gas output in solar greenhouse of solar biogas system in Xuzhou, Jinan, Lhasa, Harbin, Shanghai, Ningde, Chengdu and other typical areas were calculated by using typical year by hour meteorological data. Except for Harbin which cannot produce biogas for a period of time from January to March, other areas can produce biogas continuously. The total annual biogas production capacity is about 287m^3 in Lhasa, 285m^3 in Ningde, 276m^3 in Jinan, 274m^3 in Shanghai, and 262m^3 in Chengdu, and only 229m^3 in Harbin due to a period of no gas production.

The heat transfer model is based on many assumptions, for example, many parameters of the model are set to be constant. This model can be used to verify the effect of biogas fermentation assisted by simple solar greenhouse, to provide a reliable heating scheme for biogas fermentation, and to analyze the adaptability of biogas fermentation in various places. In order to further propose practical measures to improve the effect of biogas fermentation, it is necessary to optimize the model, and the influence of feed temperature and ground heat transfer should be further considered.

This research has been supported by the China National Key R&D Program during the 13th Five-year Plan Period under Grant No. 2018YFD1100700.

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