DESIGN AND NUMERICAL ANALYSIS OF A COMPOSITE SYSTEM OF A HOUSEHOLD BIOGAS DIGESTER WITH PRETREATMENT

by

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The rural household biogas digesters are studied in this paper, and numerical analysis is used to simulate the effects of light climates in the cold season and the heat of sunlight on the temperature distribution in the pool. The numerical results show that the uneven distributions of light intensity and temperature in the biogas digester have a great influence on its cumulative gas production. The central area has a significant heat collection effect, the inner wall is weaker, and the temperature near the top is slightly higher than that in the lower area, and the vertical temperature changes in a decreasing trend. Aiming at the different photoclimatic conditions of the household biogas digester and the uneven heat collection and temperature distribution in different periods, the traditional slag pumping work is cumbersome, and the utilization rate of the biogas residue is low, so a new household with pretreatment is proposed. An intelligent temperature control system is designed for the biogas tank to analyze the adverse effects of straw fermentation at low temperature, insufficient gas production and low resource utilization.

Key words: *biogas digester, temperature control system, simulation; design*

Introduction

Energy shortage has become a major problem in global economic development, and many technologies were appeared for energy harvesting [1, 2]. On the other hand, a large amount of biomass straw in China was wasted due to lack of proper treatment. The traditional household buried biogas digesters have unstable gas production and low gas production rate in the cold season, China's rural energy structure requires low cost. In order to slow down the excessive consumption of conventional energy by heating in winter, the proposal of combined heating system of biogas and solar energy has attracted much attention from the energy industry [3-8]. Pretreatment of straw before fermentation was a common method to improve straw degradation efficiency and gas production rate. Wang *et al.* [9] used corn stalks as fermentation raw materials and used a fluidized bed pyrolysis reactor to conduct thermochemical pretreatment at 200 °C. Wang *et al.* [10] used corn and cow dung as raw materials to study the best conditions for anaerobic fermentation in a medium and low temperature environment through

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static experiments. Li *et al.* [11] proposed a combined biogas project heating system of solar energy, air source heat pump and power generation waste heat. Sun *et al.* [12] used experimental methods to study the arrangement of heat exchangers to ensure the uniformity of temperature distribution in the fermentation tank. In recent years, many experts and scholars conducted in-depth research on how to improve the winter gas production rate of biogas, to shorten the straw degradation cycle, and to conduct constant temperature fermentation in the pond. However, there were few research reports on the comprehensive system design of the low gas production rate of the biogas digester. According to the problems of unstable gas production and low gas production rate in the cold season of traditional household buried biogas digesters, this paper uses a numerical method to simulate and analyze the natural lighting conditions of traditional biogas digesters in winter (cloudy and sunny) to obtain the temperature distribution and change trend of buried biogas digesters. In view of the uneven temperature distribution of traditional household biogas digesters, the cumbersome work of slag extraction, and the low utilization rate of biogas residue (liquid), a design scheme of a new intelligent temperature control system for household biogas digesters with pretreatment is proposed.

Numerical analysis of the traditional household biogas digester

In order study numerically the effects of daylighting and heat collection simulation on the traditional household biogas digester, we give the following assumptions: the heat and mass exchange between the enclosure structure and the outside are ignored, and no biogas leak occurs, the change in cloud cover and solar radiation is ignored, and the light climate zone coefficient is 1.1, the bottom of the pool is made of concrete (reflectance 0.5), the inner wall surface of the pool is made of bricks (reflectance 0.8), and the top of the pool is a tempered glass plate (reflectance 0.9). The bottom plate is the reference base for daylighting. The model was shown in fig. 1. The illuminance distributions of different light climates (cloudy and sunny) in the cold season are shown in figs. 2 and 3.

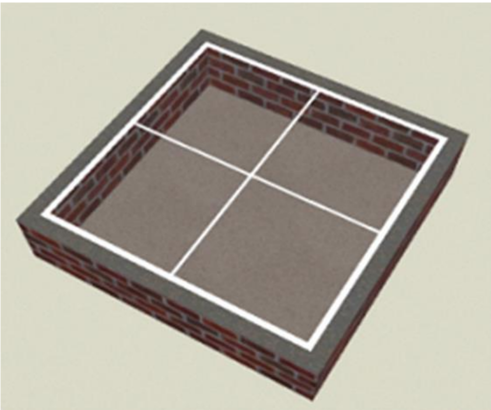

Figure 1. Biogas digester model

Figures 2 and 3 reveal that the uneven distribution of light and temperature in the pool. The heat collection in the central area along the longitudinal axis of the pool is observed, while the inner wall side is weaker, and the temperature in the area near the top (near the ground) is slightly higher than that in the lower area (near the bottom of the pool), and the longitudinal temperature change shows a decreasing trend. In the cold season, the illuminance of the whole cloudy day (8:00~17:00) is weaker than that of the whole sunny day (8:00-18:00), and the solar radiation time of the whole cloudy day is two hours shorter than that of the sunny day. All sunny days (8:00~18:00) have sufficient sunshine, and the sunlight at the bottom of the pool changes significantly. The light distribution in the pool changes with the change of the solar radiation direction, and the illuminance gradually increases from the inner wall side to the middle of the pool. From 8:00 to 12:00, the light on the west side wall is better, and the east side wall is darker. As the direction of solar radiation changes, the illuminance in the pool

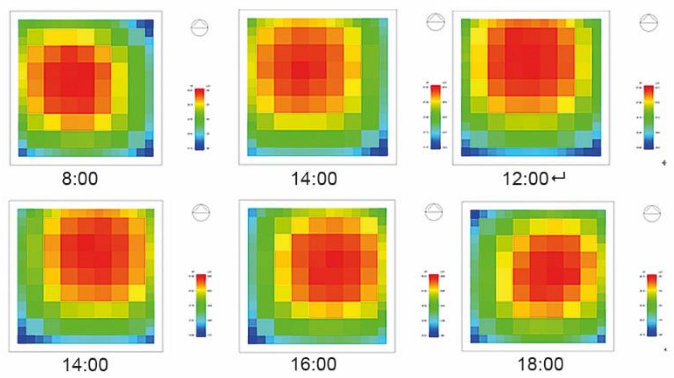

Figure 2. Cloud map of natural lighting distribution in all sunny days (8:00~18:00)

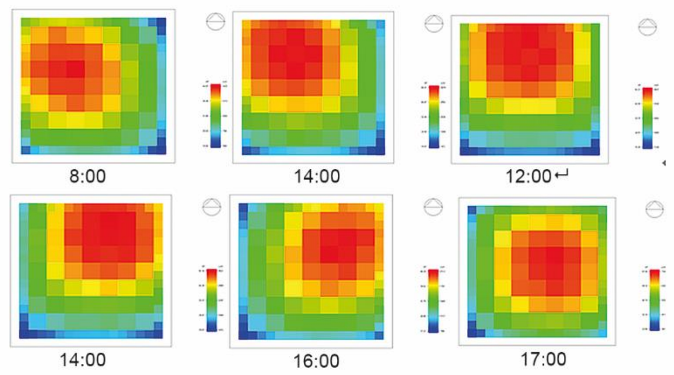

Figure 3. Cloud map of natural lighting distribution in a full cloudy day (8:00~17:00)

gradually changes slowly to the north side. At about 12:00 noon, the area with higher illuminance moves to the north side wall area of the pool. From 12:00 to 14:00, the longitudinal axis and the north side wall area in the pool have sufficient light, and the south side wall area is relatively dark. From 14:00 to 18:00, the area with higher illuminance moves slowly from the north side wall area to the east side, and the illuminance in the east side wall area is larger. Figure 3 also shows a small uniformity of daylighting in a cloudy day (8:00-17:00) in the cold season, and the illuminance is lower than that of a sunny day, but the overall trend is similar to that of a sunny day, and the illuminance distribution trend is a symmetrical trapezoidal distribution. Furthermore, the areas with higher illuminance follows the direction of solar radiation, slowly moving from the west side wall area to the north side wall area and gradually to the east side wall area.

Figure 4 shows the illuminance change with time in all sunny days (8:00~18:00) and all cloudy days (8:00~17:00).

It could be seen from fig. 4 that under different light and climate conditions, the illuminance increases first and then decreases with time. In a sunny day, the illuminance value increases slowly from 6:00 to 9:00, and the illuminance increases sharply from 9:00 to 12:00. The illuminance value reaches its maximum at about 12:00, and then gradually decreases to

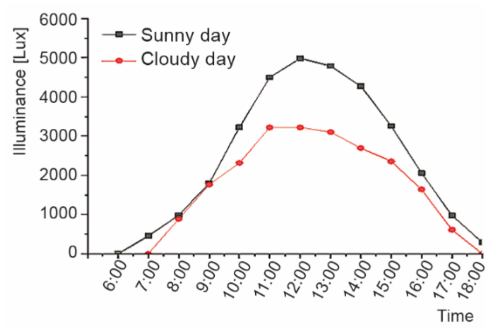

Figure 4. The illuminance change curve of all sunny days (8:00~18:00) and all cloudy days (8:00~17:00) with time

0 Lux at 18:00; the change of illuminance in a cloudy day is similar to the trend in a sunny day, but the increase in illuminance is slower than that in a sunny day, and the change in illuminance is not significant from 11:00 to 13:00, reaching the maximum value of 3223 Lux at about 12:00, the maximum difference of illuminance in a full sunny days and a full cloudy days is 4982 Lux and 3223 Lux respectively. At 12:00, 13:00 and 14:00, the difference in illuminance between a full sunny day and a full cloudy day is particularly significant, the difference is about 2063 Lux, 1686 Lux, and 1584 Lux, respectively. At any point in time, the illuminance of a full cloudy day is smaller than that of a full sunny day, and the illuminance value is quite different.

Intelligent temperature control system for household biogas digesters with pretreatment

In view of the uneven temperature distribution of the traditional household biogas digester, there are many shortcomings, *e.g.*, the cumbersome work of slag extraction, and the low utilization rate of biogas residue (liquid), therefore, a new household biogas digester with an intelligent temperature control system is much needed, fig. 5, which includes a raw material pretreatment system, an intelligent temperature control system and a biogas residue treatment system.

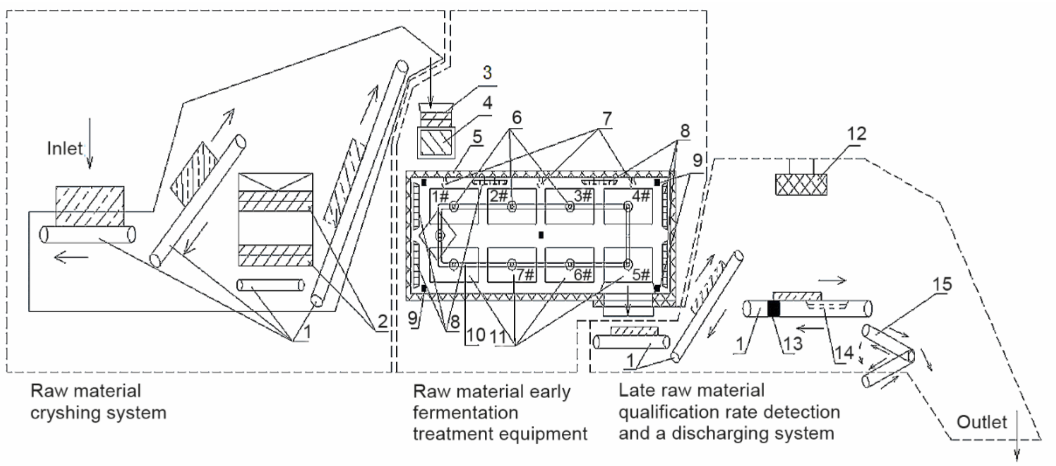

Figure 5. Schematic diagram of raw material pretreatment system structure; *1 – material conveyor, 2 – material shredder, 3 – material shredder II, 4 – storage box, 5 – insulation layer, 6 – intelligent control rotator, 7 – intelligent humidifier, 8 – intelligent radiation heater, 9 – intelligent temperature and humidity sensor, 10 – guide rail, 11 – intelligent rotating material reaction box, 12 – infrared temperature detector, 13 – intelligent quality detector, 14 – intelligent humidity detector, and 15 – intelligent rotary conveyor*

According to fig. 5, the raw material pretreatment system includes a raw material crushing system, a raw material early fermentation treatment equipment, a late raw material qualification rate detection and a discharging system. The raw materials (such as animal manure, straw, *etc*.) are crushed into pieces in the material shredder II through the material conveyor – 1, and enters the storage box – 4 for storage. The discharge port valve of the storage box – 4, is connected to the central control system, which will send an *open* command, and the stored raw materials are sent into the intelligent rotating material reaction box – 11. After being fully loaded, it would be braked and controlled by the intelligent regulating rotators – 6, on its both sides, and move on the guide rail – 10. At the same time, the intelligent temperature and humidity sensor would collect data, and the central control system would intelligently control the early fermentation pretreatment operation of raw materials, which would be transported by the material conveyor – 1, and detected and collected by infrared temperature detector – 12, intelligent quality detector – 13, intelligent humidity detector – 14, *etc*.

Additionally, an intelligent temperature control and a mass transfer mixing system are needed. In the biogas digester, due to the different densities of the substances involved in the anaerobic reaction, there would be stratifications and uneven distribution, resulting in a reduction in the contact area between the raw materials and the bacterial flora, slow fermentation and low gas production rate; In addition, the temperature in the pool is greatly affected by the ambient temperature [13-16]. The intelligent temperature control and mass transfer stirring system (including stirring device, gas leakage prevention device) is shown in fig. 6. The stirring device includes a sleeve-type transmission shaft – 3, and a number of stirring claws – 19. The schematic diagram of the system structure is shown in fig. 7, which includes the enlarged structure of the upper part of the stirring device, and the partial enlarged structure of the stirring claw.

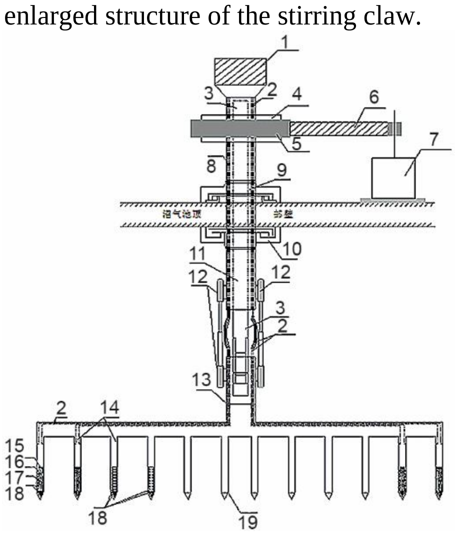

Figure 6. Schematic diagram of the structure of the intelligent temperature control mass transfer stirring system; *1 – liquid pressurizing device, 2 – liquid conveying hose, 3 – telescopic transmission shaft, 4 – transmission gear, 5 – transmission gear protection housing, 6 – transmission belt, 7 – electric motor, 8 – upper sleeve shaft, 9, 10 – biogas digester gas leakage prevention device, 11 – inner shaft, 12 – lifting hydraulic control device, 13 – lower sleeve shaft, 14 – chemical storage tank, 15 – temperature sensor, 16 – electric heating rod, 17 – jet cooling nozzle, 18 – hollow hole, and 19 – stirring claw*

The schematic diagram of the transmission structure of the stirring device is shown in fig. 8. When the motor works normally, the transmission gear drives the stirring device and the surface part of the top wall of the biogas tank to rotate, that means that the sleeve type transmission shaft and the lifting hydraulic control device rotate synchronously to drive the stirring claws to rotate, and the stirring claws to proceed normally for the stirring work. The lifting function of the stirring pawl is to use the lifting hydraulic control device to drive the lower sleeve shaft to rise and fall, and then to control the lifting in the tank.

The biogas residue treatment system is shown in fig. 9. The biogas residue is sucked out of the biogas tank by the biogas residue pump – 1, through the biogas residue conveying pipe – 2, and it is transported into the biogas residue storage tank – 3, to achieve static separation treatment. The biogas residue is kept and stratified in the biogas residue storage tank – 3, and the biogas slurry is filtered and processed by the biogas residue filter – 4. Among them, the liquid contained in the biogas residue is transported to the biogas slurry storage tank – 6, through the drainage plate – 7, and the biogas slurry conveying pipe – 5, to form the liquid biogas fertilizer. Meanwhile the solids contained in the biogas residue are stored in the upper part of the biogas residue filter – 4, and are transported by the material conveyor – 1, to the biogas residue drying oven – 8, for drying treatment to form dried biogas fertilizer.

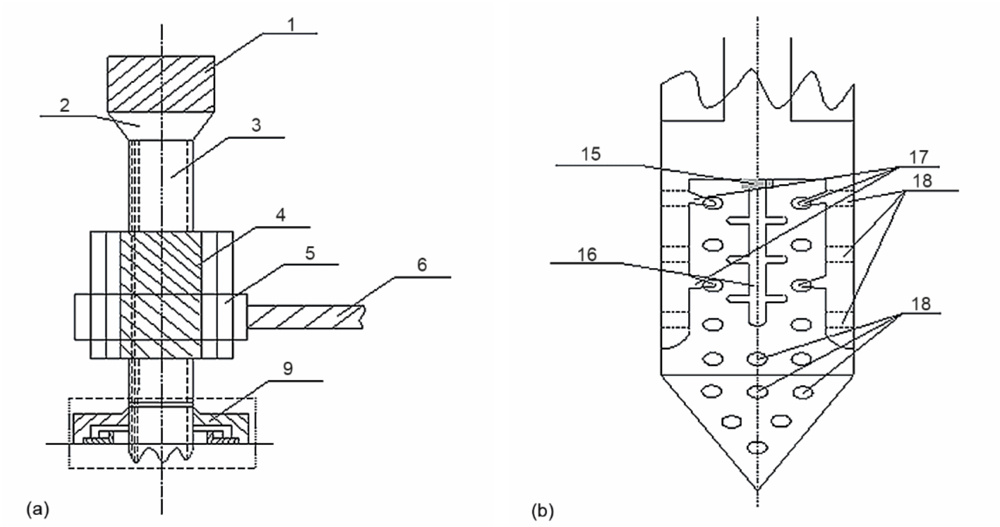

Figure 7. Schematic diagram of system structure; (a) the enlarged structure of the upper part of the stirring device and (b) the partial enlarged structure of the stirring claw;
1 – liquid pressurizing device, 2 – liquid delivery hose, 3 – sleeve type transmission shaft, 4 – transmission gear, 5 – transmission gear protection housing, 6 – transmission belt, 9 – biogas digester gas anti-leakage device, 15 – temperature sensor, 16 – electric heating rod, 17 – jet cooling nozzle, and 18 – hollow hole

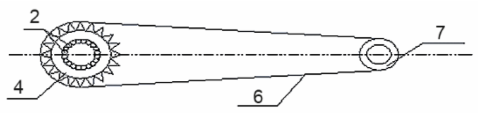

Figure 8. Schematic diagram of the transmission structure of the stirring device; *2 – liquid delivery hose, 4 – transmission gear, 6 – transmission belt, 7 – electric motor*

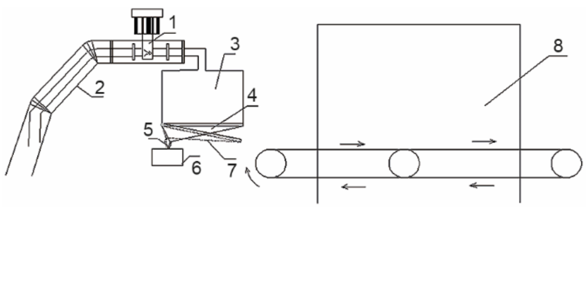

Figure 9. Schematic diagram of biogas residue treatment system;
1 – biogas residue pump,
2 – biogas residue conveying pipe,
3 – biogas residue storage tank,
4 – biogas residue filter,
5 – biogas slurry conveying pipe,
6 – biogas slurry storage tank,
7 – drainage plate, and
8 – biogas residue drying oven

Discussion and conclusion

Thermal response due to a sudden temperature jump [17-20] might be considered in future, and the sliding mode control [21-24] can also be used in our intelligent temperature control system, intelligent nanomaterials for solar energy harvesting [25] is also a promising technology for design of a rural household biogas digester. The convergence analysis of the numerical algorithm can be dealt with in a similar way as that in [26, 27].

In the case of natural lighting in a full cloudy and a full sunny day, the illuminance value reaches its maximum at about 12:00, and the direction of the central area with high illuminance moves from the west to the north and then to the east. The illuminance gradually decreases from the middle to the surrounding area of the biogas digester, forming a circular channel through which heat is sent outwards, indicating that the lighting uniformity is not good; Compared with a full sunny day, a full cloudy day sees large difference in illuminance at 12:00, 13:00, and 14:00, and the shorten illumination time. The intelligent temperature control system for household biogas digesters with pretreatment includes a raw material pretreatment system, an intelligent temperature control mass transfer mixing system, and a biogas residue treatment system to realize the integrated intelligent temperature control of raw material pretreatment, constant temperature anaerobic fermentation, and organic fertilizer.

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