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Experimental Study of a Thermal Storage Technique with Phase Change Material Closure for Solar-Biogas Hybrid Fermentation System

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Abstract

It is a key energy policy in China that developing biogas technology is to crack energy short problem in its rural areas. A pilot water thermal storage tank with phase change material insulation closure was developed to collect the daily solar energy for satisfying the heat loading required by biogas fermentation tank which should keep at about 35°C optimum efficient fermentation temperature in each winter day. The thermal performance of the water thermal storage tank was investigated under the different typical local winter air temperatures of 10°C, 5°C and 0°C. Both the numerical and experimental data demonstrate that the phase change material paraffin layer improves the thermal storage time of the tank effectively. This suggests that the proposed water thermal storage tank with phase change material insulation closure could be a promising heat storage device utilized towards solar-biogas hybrid system in rural regions of **the middle** and **lower reaches of Yangtze river**.

Keywords: Solar energy; Biogas fermentation; Heat storage; Phase change insulation closure

Abbreviations

h(latin symbol): Coefficient of Convective Heat Transfer; T(latin symbol): Temperature; t: Time; u(latin symbol): Velocity; x(latin symbol): x Symbol; y(latin symbol): y Symbol; z(latin symbol): z Symbol; j(latin symbol): Polyurethane; p(latin symbol): Paraffin; w(latin symbol): Water.

Introduction

In order to solve energy shortage in the rural regions, it has been a published energy policy in China to encourage the applications of biogas technology widely [1-3]. Since biogas fermentation tanks stop to yield methane or with lower biogas production efficiency when they runs under the low ambient temperature below 5°C, it meets the environmental limitation to apply the traditional biogas devices in the region with cold winter, especially in the middle and lower reaches of **Yangtze river** [4-8]. Therefore, it is a key problem how to provide a suitable thermal environment for satisfying biogas fermentation with high efficiency in winter.

Among different thermal supporting technologies, solar is considered as a promising and economic energy to be intensively investigated. Wu Lei et al., built a pilot experimental fermentation device heating by solar and studied biogas production under winter weather conditions. The results show that the device in winter could maintain the fermentation temperature around 25°C. Li Jinping et al., designed and constructed a new type of solar heated biogas system used in Lanzhou, the northwest region of China. This system can operate steadily with the parameters of the average daily gas production 1.422 m^3, pool capacity gas production rate of 0.614 m^3/m^3d and average methane content of 51.4%. Li Jicheng et al., proposed an anaerobic fermentation system by uniting the solar energy and biomass boiler, which was utilized to ensure the gas production rate of large-scale biogas fermentation tank under normal conditions in winter. G.KOCAR et al., studied the difference performance of a 5 m^3 biogas fermentation tank with and without solar energy in three different climate zones under two different cities in Turkey. The results showed that biogas consumption which be used to heat biogas reactor decreased by about 19% after using solar heating systems, which means that the potential for biogas production has been improved. Dai et al., investigated suitable collector area to achieve the appropriate temperature in biogas fermentation, but he only studied the collector area corresponding to 25°C fermentation temperature. Charlotte Rennuit et al., studied biogas fermentation pool model includes required solar heat collection according household demand amount of energy annually in Hanoi, Axaopoulos et al., designed a solar powered household biogas fermentation system and built its mathematical model, using flat-plate collectors as an integral part of the roof structure of a swine manure digester. It demonstrated the mathematical model can predict the energy change of solar heating reactor. In order to predict the **temperature distribution** of fermentation reactor during steady-state conditions, Andreas Ch. Yiannopoulos et al., designed a solar-biogas hybrid system and built its mathematical model. Obviously, there is still lack of a valuable biogas technology directly applied in the middle and lower reaches of Yangtze River.

In this paper, a kind of water thermal storage tank with phase change material (PCM) insulation closure is developed to satisfy the thermal demand of a solar-biogas hybrid system working around 35°C with high fermentation efficiency in the local winter season. The thermal storage time of this kind of tank was numerically and experimentally investigated.

System Description

In this study, a solar-biogas hybrid system was designed to be used for investigate its thermal performance in the rural region of HE

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country, Anhui province. The system schematic is shown (Figure 1). The solar collector is used to absorb solar irradiation to heat water daytime. The heated water is stored in the heat storage water tank whose closure is made of paraffin phase change material. The two-phase anaerobic digestion device consists of fermentation tank, hydrolysis acidification tank and other auxiliary parts such as water sealer, dehydrator, wet gas storage tank and dry desulfurizer. Here the fermentation tank is set to produce 5 m^3 biogas a day under the condition of 35°C fermentation temperature. The thermal energy required by the fermentation tank is supplied by the hot water which runs from the heat storage tank to middle temperature heat storage tank and provides heat through heat exchanger in the fermentation tank.

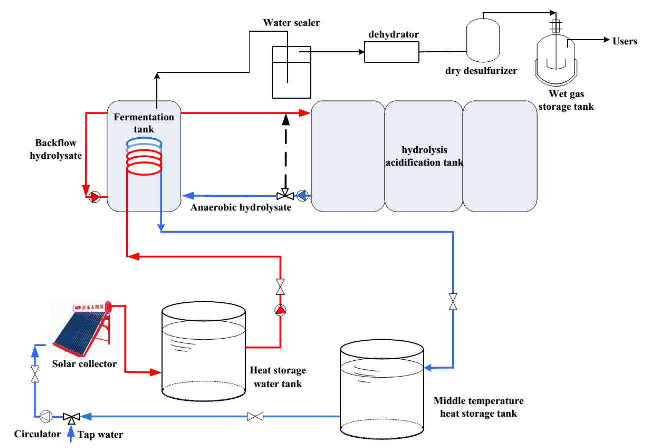

Figure1: Schematic diagram of solar-biogas hybrid system.

The configuration of heat storage water tank with phase change material closure used in the system is shown in figure 2. There are 3 layers of insulation materials on each side. The inner is the polyurethane insulation with 50 mm thickness. The middle is the paraffin wax RT54 as PCM with 30 mm thickness. The outer is also the polyurethane with 200 mm thickness. Its volume is 1 m^3 to provide 55°C hot water for heating biomass liquid in the fermentation tank.

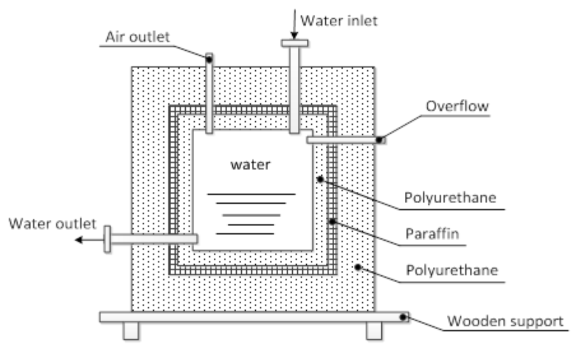

Figure 2: Structure of the water thermal storage tank with PCM insulation closure.

The thermal properties of paraffin and polyurethane are listed in table 1. These data will be used for the flowing numerical thermal performance assessment for the tank.

Thermal Analysis

Numerical model and boundary conditions

Based on the desktop of Fluent (ver.6.3.26), the numerical mode was built according to the parameters stated in the upper section. Here, with regard to the outer wall of 200 mm thickness of polyurethane, the heat transfer coefficient between the wall and outside air and free stream temperature are defined under the third boundary condition. The following basic assumptions were adopted [1] liquid paraffin is incompressible Newtonian fluid and its flow is laminar [2] only consider the changes of fluid density in the buoyancy lift, changes of density is only relative to the volume part in momentum equation, density in the rest part is constant, namely Boussinesq hypothesis [3] density and thermal conductivity of paraffin is constant; [4] there are solid phase zone, liquid-solid fuzzy area and liquid phase area in the melting process of paraffin, where the liquid-solid fuzzy area is considered as porous media, the porous proportion equals liquid proportion [9].

Descriptions	Paraffin	Polyurethane
Reference density	760 kg/m³	42.6 kg/m³
Specific heat capacity	2400 J/kg K	2380 J/kg K
Thermal conductivity	0.2 W/m K	0.04 W/m K
Melting temperature	328K	-
Latent heat	256000 J/kg	-
Dynamic viscosity	0.01 kg/m s	-
Coefficient of thermal expansion	6×10^{-4} K^{-1}	-

Table 1: Thermophysical Parameters values of paraffin and polyurethane.

The solidification & melting model is also sued to solve problem of phase change heat transfer. The related governing equations are simply listed as the following group of Equation (1), Equation (2), Equation (3) and Equation (4), which are published in the literature of FLUENT 6.3 User's Guide. The enthalpy of the material is computed as the sum of sensible enthalpy h and the latent heat ΔH, which is defined as

$$h = h_r + \int_{T_r}^{T} c_p dT + \Delta H \rightarrow (1)$$Where the sensible enthalpy h is figured out through parameters of latent heat ΔH reference temperature Tr, specific heat at constant pressure cp and reference enthalpy hr. The latent heat content ΔH is written in terms of the latent heat of the material L. The latent heat content can vary between zero (for a solid) and L (for a liquid).$\Delta H = \beta L \rightarrow (2)$Where β is the liquid fraction and can be defined as $\beta = \begin{cases} 0 & T < T_s \\ (T - T_s)/(T_l - T_s) & T_s < T < T_l \\ 1 & T > T_l \end{cases}$

$\rightarrow (3)$Where Ts is the solidus temperature and Tl is the liquidus

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temperature. For solidification/melting problems, the energy equation is written as

$$\rho\left(\frac{\partial h}{\partial t}+u_x\frac{\partial h}{\partial x}+u_y\frac{\partial h}{\partial y}+u_z\frac{\partial h}{\partial z}\right)=\frac{k}{c_p}\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}\right)+\frac{\rho}{c_p}\frac{\partial(\Delta H)}{\partial t}\rightarrow(4)$$

Where H is enthalpy, ρ is density, (u_x, u_y, u_z) are three components of fluid velocity and k is the turbulence kinetic energy.

The boundary conditions of numerical simulations were based as following data: x=0.78 m, h=25 W/m^2 K, T=T_a; x=-0.78 m, h=25 W/m^2 K, T=T_a; y=0.78 m, h=25 W/m^2 K, T=T_a; y=-0.78 m, h=25 W/m^2 K, T=T_a; z=0.78 m, h=25 W/m^2 K, T=T_a; z=-0.78 m, h=25 W/m^2 K, T=T_a. And the initial conditions were defined as t=0 S, u=0 m/s, T_w=T_p=331 K, T_j=(331+T_a)/2.

Temperature variations of PCM layer and water under different ambient air temperature

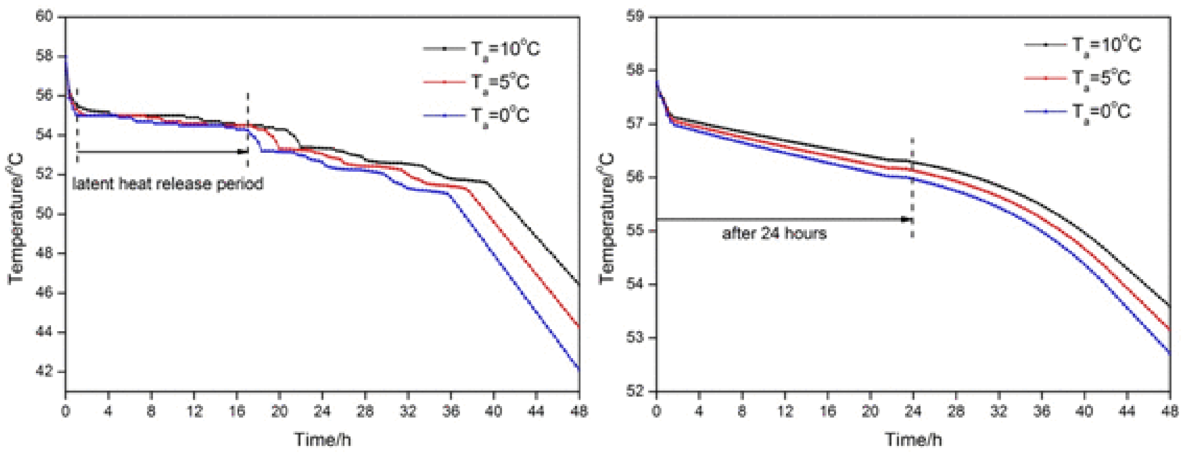

Figure 3: Temperature variation in the tank (Ta is ambient air temperature), where (a) In the paraffin layer and (b) In the water.

In order to assess the thermal performance of the thermal storage tank, the numerical results of temperature variations for paraffin layer and water are shown in figures 3 (a) and (b) respectively [10]. It is obvious that there exits three similar and distinct periods for three ambient temperatures when the water storage tank is in natural cooling process. In figure 3 (a) T_a=0°C as the example, the first is the sensible heat release period before 240 minutes when water and paraffin layer in liquid phase keep to be cooling down from 58°C to 55°C. Since the water thermal storage tank is filled with 58°C hot water which is supposed to be provided by the solar flat collectors at the initial state. Then the paraffin layer keeps around 55°C of phase change temperature when its latent heat release period. This is the second period which lasts from 240 minutes to 1120 minutes [11]. The liquid state of Paraffin layer is changed into solid state. In the third interval, the temperature of paraffin layer in solid state drops quickly and linearly. As for the water in the tank, its temperature drops quickly in the first period. Then its temperature reduces slowly, but still keeps above 55°C in the second period. In the third period, the water temperature drops quickly too [12]. Thus the water thermal storage tank can maintain 55°C for more than 24 hours. It demonstrates that the PCM insulation closure improves the thermal storage capacity of the water tank [13].

Experimental validation

In order to validate the upper numerical results, a pilot experimental device was built according to the physical parameters of the water thermal storage tank as shown in figure 2. The measurement system is shown in figure 4. It includes a 16 channels temperature measuring device and an electric heater. The multi-channel device was used to record temperature variations in 12 specific positions which were located at 1 point in water and 1 point for the ambient air as well as the tank 6 surfaces and 4 adjacent points between different insulation layers. And the heater was also used as the thermal source to surely heat the paraffin layer in liquid state when the tank was filled with 58°C hot water [14].

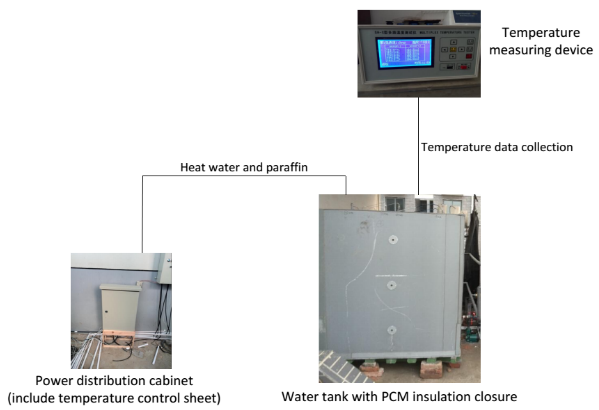

Figure 4: A pilot experimental setup for the thermal performance test of the water thermal storage tank.

At the beginning of the experiments, both the water in the tank and the paraffin layer are heated to 58°C. Then the water tank keeps in the natural cooling state. And the temperature measuring device is open to automatically record the temperatures at 12 specific points in every 3 minutes [15].

The experimental and numerical results are illustrated in figure 5. Here T_w is water temperature, and T_p is paraffin temperature which is considered as the average temperature at the two sides of the paraffin layer. And the air environment temperature was 15°C. The average heat loss of water is about 98 W during 24 hours. In figure 5, it is also shown that there exists the three periods for paraffin layer during the water tank in cooling process. The phenomenon of the three periods is similar to that shown figure 3. During the latent heat release period, the paraffin layer changes from liquid to solid and the period lasts about 28 hours. Both the numerical predicated and the experimental measured water temperatures are over 55°C [16]. Their average values in 24 hours are 56.9°C and 56.1°C, respectively. Obviously, the numerical water temperature is hotter than that measured in experiment. It states that the actual heat loss from the water tank is larger than that figured out in the numerical simulation [17]. It may be due to humidity effect. In the case of air temperature 10°C, 5°C and 0°C, the heat loss of water will increase 12.4%, 22.8% and 33.2% compared with the heat loss in the average ambient air temperature 15°C after the water storage tank keeps in the natural cooling process of 24 hours. The values of the corresponding heat loss are 110 W, 120 W and 131 W separately.

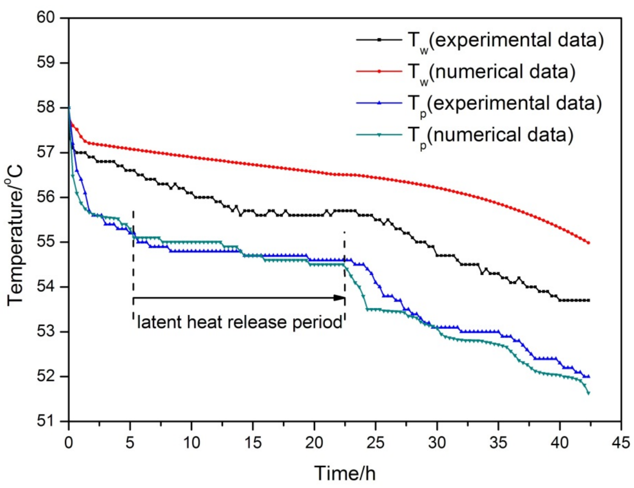

Figure 5: The measured temperature variations of water (T_w is water temperature, T_p is paraffin temperature).

In order to assess the thermal performance of the water thermal tank more comprehensively, the experiments have been carried out to continuously monitor the temperature variations of PCM layer and water in 90 hours. The experimental results are illustrated in figure 6. The latent heat release period could maintain about 28 hours similar to that shown in figure 5. Meanwhile both the temperature of paraffin layer and water in tank keep temperature over 55°C. The heat loss of water during this period is about 97 W. When paraffin layer becomes in complete solid, it is in the third sensible heat release period [18]. In this case, both water and paraffin temperatures drop quickly, and the average heat loss of water during this period will be 125 W.

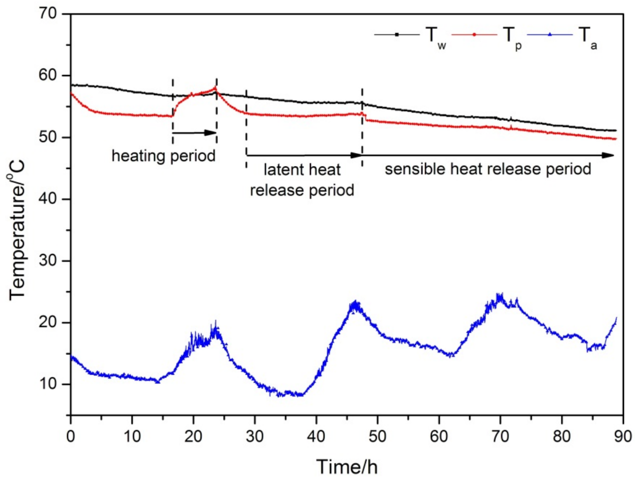

Figure 6: Temperature variations of T_w, T_p, T_a.

Conclusion

This work focuses on the thermal heat storage performance of a water tank with PCM insulation closure which aims to satisfy the thermal demand form a solar-biogas hybrid system in the **middle and lower reaches of Yangtze river**. The experimental data certificate that this kind of the water thermal storage tank can keep 55°C hot water for more than 28 hours in the case of 15°C ambient air temperature. The average heat loss of water is about 98 W during 24 hours. The simulations suggest when ambient air temperature is 10°C, 5°C and 0°C, the heat loss of water increases 12.4%, 22.8% and 33.2% respectively compared to the average ambient air temperature is 15°C after natural cooling process of 24 hours. The values of the corresponding heat loss are 110 W, 120 W and 131 W separately [19,20]. When the paraffin layer is completely in solid state, the heat loss from water increase to 125 W, it shows that the phase change insulation closure can reduce heat loss effectively. To gain a better understanding of the thermal performance of the water thermal storage tank used on solar-biogas hybrid system in the local weather, it is necessary to make further study about the operating effect and thermal performance of the whole solar-biogas hybrid system in experiment.

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