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Effect of solar irradiance on photo biochemical transformation process of direct absorption methane digester

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ABSTRACT

Direct absorption methane digester can accomplish the coupled process of solar heat collection and photo and biochemical reaction of microorganisms simultaneously. In present work, a numerical model was developed to determine a tool to investigate the photo biochemical transformation process for developing engineering analyses, which is a coupled one of the simplified ADM1 model and the heat and mass transfer model. The model was validated by experimental data from two groups of different experiments. The effect of solar irradiance on the photo biochemical transformation process was also investigated by the model. The results show that a good agreement has been obtained between experimental data and simulations, which can be achieved in most of time. The study found that increasing solar irradiance is an effective method to improve the biogas production rate of direct absorption methane digester. With the solar irradiance increasing, the volume average temperature increases and the rates of biogas production, substrate reaction and total propionate all turn bigger. The effect of solar irradiance on biogas production rate is bigger than the one on the rate of propionic acid. In order to increase the heat storage of digester, the slurry surface evaporation of digester should be restrained.

1. Introduction

With the continuous improvement of energy and environmental awareness of people, more and more attention has been paid to development and utilization of renewable energy in the world [1]. As a big agricultural country, the output of agricultural waste in rural areas of China is at an annual rate of 5–10%, which will increase to 50 billion tons by 2020 [2]. Biogas engineering can recycle and deal with waste, which is an important link to carry out the model of sustainable agricultural development.

The production from biogas engineering is a kind of anaerobic fermentation of biomass. There are three kinds of fermentation technologies for anaerobic digestion: low temperature (15 °C), medium temperature (30–38 °C) and high temperature (50–55 °C) [3]. Anaerobic digestion of medium temperature has been shown to be more widely used owing to its better economy. When the temperature in the fermentation system is much lower than the standard one, the efficiency of fermentation will be greatly affected [4].

The research focus on biogas engineering is to convert clean energy into fermentation system, which is propitious to improve the fermentation temperature and maintain biogas production efficiency under low temperature condition. Solar energy is an economical source for heat collector, considering its universality of distribution. Solar tubular collector is a kind of heat collector that uses tube to absorb solar energy for heating hot water [5]. Lu et al. [6] utilized a united system of solar collector and heat storage device filled with PCM to improve the fermentation efficiency of biogas devices, and the results showed that the application effect of combined system in summer and autumn is far better than the one in winter. Solar greenhouse is a structure covered by a transparent device in order to use solar energy to control temperature, humidity and other parameters [7]. Perrigault et al. [8] utilized the combined device of tubular collector and greenhouse to heat the digester in cold climate, and the simulation results showed that the greenhouse has big effect on improving the thermal performance of digester, but the slurry temperature was unable to reach the optimum fermentation temperature during most of time in winter. Solar air source heat pump is also a good heat collecting form in methane gas project [9]. Curry et al. [10] proposed to heat the digester with an air source heat pump obtained from solar heat gains of a greenhouse, and a 3-D model of the building with surrounding was built to analyze the thermal performance of the system. The result showed that it can maintain the fermentation temperature in the coldest month of the year with a 2 kW_e air source heat pump.

Most of the biogas heating systems are not enough to only rely on

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Nomenclature

c	specific heat of media, J/(kg K)
k	thermal conductivity of media, W/(mK); extinction coefficient, m^{-1}; pipe resistance coefficient, m^3/(kg h Pa)
F	share function
h	convective heat transfer coefficient, W/(m^2K); convective mass transfer coefficient, m/s
L	latent heat, J/kg
Nu	Nusselt number, -
Pr	Prandtl number, -
Le	Lewis number, -
M	molar mass, kg/mol
H	depth, m
S	concentration of soluble components, kg_{COD}/m^3
q	biogas production, g/(kg h)
R	gas law constant, Pa L/(mol K)
T	temperature of media, K
I	radiant intensity, W/(m^2·sr)
E	radiant energy, W/m^2
G	evaporation rate, g/(m^2 s); concentrations of gaseous component, kg_{COD}/ m^3
RD	radiative transfer factor
Gr	Grasshof number, -
B	mass exchange number, -; heat exchange number, -
p	pressure, Pa
y	molar mass fraction, -
X	concentration of particulate matter, kg_{COD}/m^3
V	outgas flow rate, mol/h
K	Henry's law constant, mol/(L Pa)

Greek letters

ρ	density of media, kg/m^3
μ	$\mu = \cos\theta_i$
Φ	source term, W/m^3
θ	zenith angle of solar irradiance, -; concentration difference, kg_{COD}/m^3
γ	reflectivity of surface, -
ε	emissivity of surface, -; ratio of the biogas slurry volume, -
σ	Stefan–Boltzmann constant, W/(m^2 K^4)
ρ	density, kg/m^3
Y	mass fraction of media, kg/kg
φ	relative value, -
α^1, α^2	compared parameter value and the standard value, -
δ	thickness of air layer, m
Ω	stereoangle, -
τ	time, h
χ	kinetic rate, kg_{COD}/(m^3 h)
η	stoichiometric coefficient

Subscript

l	liquid
cn	conduction
op	opaque
∞	Infinity
s	surface
g	glass; gas
m	mass
∩	scattering
⊥	direct
mix	mixed
a	air
c	critical
b	saturated
sd	solid
pro	propionic acid
ac	acetic acid
IC	Inorganic carbon

solar energy considering the problem of heating at night, though many systems have the regenerator. Multisystem heating modes have been utilized to maintain the temperature of methane gas project [11,12]. Li et al. [11] proposed a combined heating system composed of solar collector, biogas boiler and waste heat recovery system of power generation project. They concluded that the fermentation temperature was kept around 35 °C under the help of boiler and waste heat recovery system. Zhang et al. [12] used solar energy heating system and biogas boiler heating system to heat the household digesters. Three groups of contrastive experiments were made to investigate the thermal performance of the heating system. The results showed that the biogas boiler can effectively supply the rest of heat for the digesters.

The researches above achieved the cooperative utilization of a variety of renewable energy sources and solved the problem of low production rate of biogas digester under cold conditions. However the systems have some defects of complex pipeline, big energy loss and short period of efficient utilization [6–11]. In comparison, direct absorption methane system has the advantages of simple equipment and high energy utilization. Direct absorption methane system can utilize the solar absorption and scattering of media in biogas digester to improve the temperature of biogas slurry, in order to maintain the fermentation process of microorganism.

The related researches in the field of solar photothermal utilization are about experimental and theoretical analysis of salt gradient solar pond. Aramesh et al. [13] proposed a transient method for the heat extraction process in the rectangular solar ponds by a finite difference technique, whose model was verified by the experimental data. Ziapour et al. [14] investigated the potential of thermoelectric generator as a power generation system using heat from SGSP and the proposed system was evaluated through computer simulations. Solar pond is considered as a good low temperature heat source, which is widely used to industrial productions, such as desalination of sea water [15]. Mansouri et al. [16] proposed a two-dimensional numerical model to investigate the thermal characteristics of a salt gradient solar pond. The results show that the temperature of the heat storage zone can exceed 45 °C. Monjezi et al. [17] utilized experimental and theoretical methods to investigate the heat transfer process in a salinity gradient solar pond and concluded that the water can effectively use solar energy to raise its temperature and the water evaporation has big effect on the regenerative process. The previous researches indicated that direct absorption of solar energy in medium is a simple and effective way to increase its temperature, which is feasible to maintain the normal operation of fermentation system [16,17]. In addition, water evaporation should be considered for weighing the balance of energy and quality of direct absorption methane system [17].

In order to accomplish the regulation of photo biochemical transformation of direct absorption methane system, it is significant to analyze the biochemistry process in the system. Most of the current researches of the fermentation biochemistry process are about ADM1 model [18]. It has been launched by International Water Association (IWA) to simulate anaerobic digestion process [19]. Compared with the previous models, it considered the effect of multiple components of organic raw materials and intermediate product on gas production rate [20]. Many scholars have extended the ADM1 model to various forms of anaerobic fermentation, and improve the applicability of model [21–24]. Xu et al. summarized the SS-AD models obtained from