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Research Paper

Investigation on the heat loss characteristic of underground household biogas digester using dynamic simulations and experiments

Yanfeng Liu*, Yaowen Chen, Tao Li, Dengjia Wang, Daokun Wang

School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, No. 13 Yanta Road, Xi'an 710055, China

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Underground household biogas digesters (UHBD) may achieve higher gas production in cold environments by adopting heating and insulation technologies. Fully understanding the heat loss characteristic of UHBD is the prerequisite to put these technologies into application. Here, a 3-D unsteady heat transfer model coupled with the digester and surrounding soil was developed to more accurately calculate the dynamic heat loss of UHBD. The solar-air temperature (SAT) was taken as the ground surface boundary condition parameter to describe the comprehensive influences of air convection, solar radiation, and long-wave radiation. Field experiments provided the initial and boundary conditions of the model. Furthermore, the changes in the digester heat loss process and the heat response process of the soil temperature under experimental condition were measured to create a more accurate model. The comparison between the numerical and experimental results showed that the errors were minimal when adopting SAT as the boundary condition parameter, in which the maximum error of average heat flux was 5.9%. Therefore, using the SAT boundary model, heat dissipation was calculated under different fermentation temperatures, burial depths, materials, and tectonic forms. The optimal fermentation temperature was 35 °C for maximum net energy production. Heat loss exponentially decreased with increase in burial depth. Insulation could significantly reduce the heat loss of a digester. The heat loss intensity could be decreased by 67.1% when the insulation was increased to 30 mm.

1. Introduction

As the world's largest agricultural country, China generates large amounts of biomass resources (crop stalks, livestock manure, etc.) every year, and how these biomass resources will coexist as opportunities and challenges remains an open question (Chen, Yang, & Sweeney, 2010; Jiang, Sommer, & Christensen, 2011). Researchers generally believe that anaerobic fermentation could alleviate the energy crisis and reduce environmental risks (Chang, Wu, Zhou, Shi, & Yang 2014). In recent years, the biogas industry in China has rapidly developed, and the nation has a total of 41.93 million underground household biogas digesters (UHBD) and 110,000 large and

* *Corresponding author.*
E-mail address: lyfxjd@163.com (Y. Liu).
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Nomenclature

c_m	specific heat of manure, J kg^{-1} K^{-1}
V_m	volume of manure, m^3
T_m	temperature of manure, °C
$Q_{heating}$	heat supplied by the heating system, W
Q_{cover}	heat losses through digester cover, W
Q_{wall}	heat losses through digester wall, W
Q_{floor}	heat losses through digester floor, W
Q_{manure}	heat required to raise temperature of the influent manure to the operating temperature, W
c_s	specific heat of soil, J kg^{-1} K^{-1}
V_s	volume of soil, m^3
T_s	temperature of soil, °C
Q_{sol}	heat gain from solar radiation at the ground surface, W
Q_{lw}	long-wave radiative heat transfer between the ground surface and environment, W
Q_{con}	convective heat transfer between the ground surface and outdoor air, W
Q_{com}	heat transfer between the ground surface and external environment, W
$T_{sol\text{-}air}$	outdoor solar-air temperature, °C
T_{air}	outdoor air temperature, °C
h_{sur}	convective heat transfer coefficient of ground surface, W m^{-2} K^{-1}
I	solar radiation intensity, W m^{-2}
T_{sur}	temperature of the ground surface, °C
T_{sky}	sky effective temperature, °C
P_d	vapour pressure, Pa
S	sunshine percentage, %
$c_{p,water}$	water specific heat capacity, J kg^{-1} K^{-1}
C_{fc}, C_{nc}	constants for forced and natural convection
ΔT_v	difference between virtual air and ground surface temperature, °C
u	wind velocity, m s^{-1}
T_f	annual average temperature of ground surface, °C
A_w	annual temperature fluctuation of ground surface, °C
k	annual fluctuation period, h
a	soil thermal diffusivity, m^2 s^{-1}
r	radial distance, m
z	depth, m
w	soil moisture content, %
B_0	biochemical methane potential, m^3 [CH_4] kg^{-1} [VS]
S_0	influent VS concentration, kg m^{-3}
K	kinetic constant, dimensionless
q_i	heat loss intensity of different parts of biogas digester, W m^{-2}
$q_{fit}(\tau)$	fitting function of hourly heat loss of biogas digester, W m^{-2}

Greek symbols

ρ_m	density of manure, kg m^{-3}
ρ_s	density of soil, kg m^{-3}
ρ_a	density of air, kg m^{-3}
ρ_{ds}	dry density of soil, kg m^{-3}
θ	azimuth angle, °
λ	thermal conductivity, W m^{-1} K^{-1}
τ	time, s
α	absorption of solar radiation by ground surface
σ	Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
ε_{sur}	emissivity of the ground surface, dimensionless
γ	volumetric CH_4 production rate, m^3 [CH_4] m^{-3} [digester] day^{-1}
μ_m	maximum specific growth rate of micro-organisms, day^{-1}

Subscripts

m	manure
s	soil
sur	ground surface

Abbreviations

UHBD	underground household biogas digesters
EBTCS	electric boiler temperature control system
MTVS	manure temperature control system
FRP	fibreglass-reinforced plastic
RP	rubber plastic
CFD	computational fluid dynamics
UDF	user-defined function
HRT	hydraulic retention time, days
SAT	solar-air temperature
OAT	outdoor air temperature
GST	ground surface temperature

medium-sized biogas digesters as of 2015 (Academy of State Administration of Grain, 2017). UHBDs are easy to operate, maintain, and offer superior environmental and economic advantages compared with large and medium-sized biogas digesters (Song, Zhang, Yang, Feng, & Ren 2014).

The fermentation process consists of a series of biochemical reactions, and numerous factors affect biogas production. Temperature of the system is one of the most important factors that determine the digestion rate. Three fermentation processes exist, corresponding to different fermentation temperature, namely, thermophilic fermentation (45–60 °C), mesophilic fermentation (25–40 °C), and normal temperature fermentation (10–25 °C) (El-Mashad, Zeeman, van Loon, Bot, & Lettinga, 2004b). For UHBD, mesophilic fermentation is more economical (Lu, Tian, Lu, Wu, & Li, 2015). In tropical and temperate climatic areas, UHBDs could run efficiently all year round, however, in cold areas, the temperature in winter is low, resulting in a low biogas production rate (Yang, Zhang, & Li, 2012). Numerous UHBDs are either idle or abandoned because heating and hot water demands increased while the UHBD energy supply could not meet these demands during the winter (Yang, Wang, Zhang, Fu & Li, 2014).

Several technological advances have improved energy production of digesters during the winter. Hassanein, Qiu, Junting, Yihong, and Witarsa (2015) proposed a passive heating technique to increase the temperature of the biogas digesters using two solar greenhouses, one surrounding the digester and the other heating the digester inlet. The