International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 9, September- 2014

Active Heating of Floating Type Dome Biogas Plant

G. N. Tiwari[1], Poonam Joshi[1], Ravi Agrihari[1]
[1]Centre for Energy Studies,
Indian Institute of Technology Delhi,
Hauz Khas, New Delhi 1100 16, India

Ibrahim M. Al-Helal[2]
[2]Department of Agricultural Engineering College of Food & Agricultural Sciences,
King Saud University,
P.O.Box 2460, Riyadh 11451, Saudi Arabia

***Abstract* - In this paper, an attempt has been made to derive an expression for the slurry temperature of flat plate collectors integrated biogas plant. The flat plate collectors are connected in series and parallel combination to optimise the number of collectors to be in series (N) and parallel (m) for optimum slurry temperature. Effect of mass flow rate ($\dot{m}_f$), length of heat exchanger (L), heat capacity of slurry ($M_s C_s$) and number of flat plate collectors (FPC's) on slurry temperature have been studies for climatic condition of Srinagar, India by using antifreeze liquid. It has been observed that the optimum slurry temperature (~37℃) has been observed for N=8 (series) and m=5 (parallel) for 40 number of flat plate collectors. Exergy of active biogas plant has also been carried out.**

Keywords:Biogas, solar heating, flat plate collectors

I. INTRODUCTION

Biogas is a mixture of methane (CH_4) 50–70% and carbon dioxide (CO_2) 30–50%. It has a calorific value of 21–24 MJ/m^3 and it is produced at 37℃ in the absence of oxygen from slurry obtained from 50% dung and 50% water. It is clean energy and environmental friendly which can be used for cooking [1-5], lighting [5-6], motor vehicles and small scale industries [7-10] to meet local energy demand. The temperature of slurry depends on local climatic conditions namely solar intensity and ambient air temperature. The slurry in digester requires to be heated for harsh cold climatic condition to obtain the optimum slurry temperature. Basically, there are two type of biogas plant namely fixed –dome and floating – dome type biogas plant. In both cases, the slurry in digester is heated either by active method or by hot charging for harsh cold climatic condition. In an active method, a combination of flat plate collectors (FPC's) can be integrated through a coil type heat exchanger placed inside digester of floating/fixed type. The number of flat plat collectors (FPC's) depends on heat capacity of slurry with local climatic condition. Further, series and parallel combination of collectors should also be optimized accordingly.

Tiwari [11-13] have proposed design criteria for active heating of fixed dome biogas plant. Yuan [14] have observed that the heat available from solar flat plate collectors with an effective area of $2m^2$ and 8 hours operation can met heat demands of a $6m^3$digester for complete fermentation in slurry. Flat plate collectors with an effective area of 100.8 m^2 is sufficient to heat water of volume 6 ton for hot charging the slurry to ferment the slurry inside digester, Dong and Lu [15]. It has also been found that 2540 m^3 biogas is produced with increase of 11.2%. They also observed that there were 14.3% increase of pig manure energy transformation efficiency.

In this paper, we have analysed the slurry temperature of active biogas plant to optimise the number of flat plate collectors to be in series and parallel for a given total number of flat plate collector and heat capacity of slurry. Exergy analysis of active biogas plant has also been carried out.

II. THERMALMODELLING

In order to write energy balance, the following assumptions have been made:

- The floating dome type bio-gas plant is considered for thermal modelling
- The biogas plant is in quasi- steady state condition
- No stratification along the depth of the slurry in digester due to forced mode and the gas column due to low heat capacity
- Thermal heat capacity (M_sC_s) of the biogas plant materials are neglected.

Referring to Fig. 1, the energy balance equations during sunshine hours have been formulated as follows:

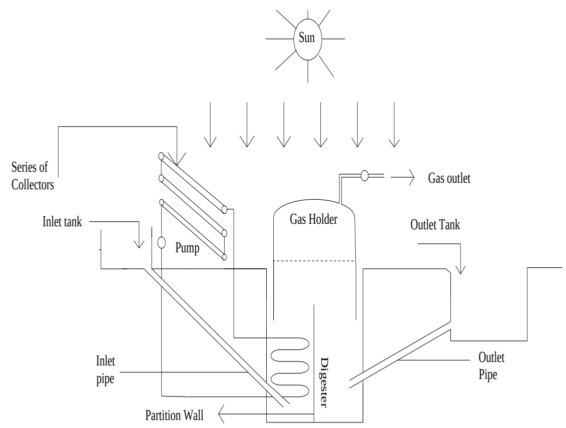

Fig.1 Schematic view of active floating type biogas plant.

Metallic biogas holder/dome:

$\propto' \left[A_h I(t) + I(t)_v \frac{A_v}{2}\right] = h_1 A_t (T_p - T_g) + h_{rps} A_h (T_p - T_a) + A'_v h_c (T_p - T_s) + h_2(t) A_t (T_p - T_a)$ (1)

Produced biogas:

$h_1 A_t (T_p - T_g) = h_3 A_h (T_g - T_s)$(2)

Slurry in digester:

$M_s C_s \frac{dT_s}{dt} = h_3 A_h (T_g - T_s) + A_h h_{rps} (T_p - T_s) + A'_v h_c (T_p - T_s) - h_4 A_h (T_s - T_\infty) - h_{sa} A'_h (T_s - T_a) - A'_h \dot{Q}_{es} + \dot{Q}_{uN}$ (3)

where,

$\dot{Q}_{es} = h_{ew}(T_s - T_a)$ is the rate of evaporation from side of dome exposed to ambient which can be neglected for simplification of modelling.

and

$$h_{ew} = \frac{0.016 h_{sa} \{P(\bar{T}_s) - \gamma P(\bar{T}_a)\}}{(\bar{T}_s - \bar{T}_a)}$$

Equations (1-3) can be combined into single equation by eliminating T_p and T_g as follows:

$M_s C_s \frac{dT_s}{dt} = F_p (\alpha AI)_{eff} - (UA)_{eff} (T_s - T_a) + m\dot{Q}_{uN}$ (4) where ,

$F_p = F_{p1} + F_{p2}$

$(UA)_{eff} = (UA)_{eff1} + (UA)_{eff2} + h_4 A_h + h_{sa} A_h'$

$F_{p1} = \frac{(UA)_L}{(UA)_L + (hA)_T}$;

$$(UA)_L = [(UA)_t + A_v' h_c];\ (UA)_t = \frac{h_1 A_t . h_3 A_h}{h_1 A_t + h_3 A_h}$$

and $(hA)_T = [h_{rpa} A_h + h_2 A_t]$

$F_{p2} = \frac{(UA)_t}{(UA)_L + (hA)_T}$;

$(UA)_{eff1} = \frac{(UA)_L (hA)_T}{(UA)_L + (hA)_T}$; $(UA)_{eff2} = \frac{(UA)_t (hA)_T}{(UA)_L + (hA)_T}$

$\dot{Q}_{uN}$ is the rate of thermal energy available from N-FPC connected in series and m is the number of rows of N-FPC connected in series, Fig.2 . Therefore there will be $(m \times N)$ FPC in active biogas plant.

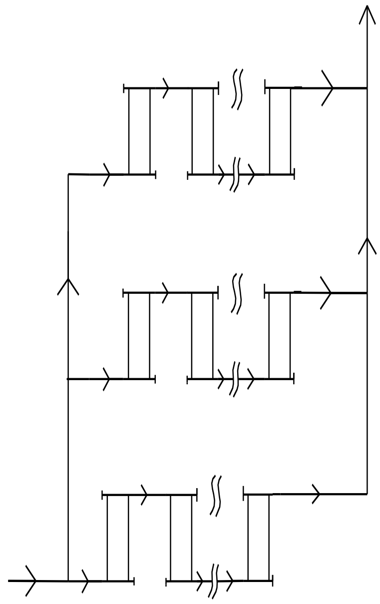

Fig.2 . Combination of N-PVT FPC connected in m rows.

Referring to Fig. 3, the energy balance for forced circulating water in coil type heat exchanger is given by

$\dot{m}_f C_f \frac{dT_w(x)}{dx} dx = 2\pi r_1 U (T_s - T_w) dx$(5)

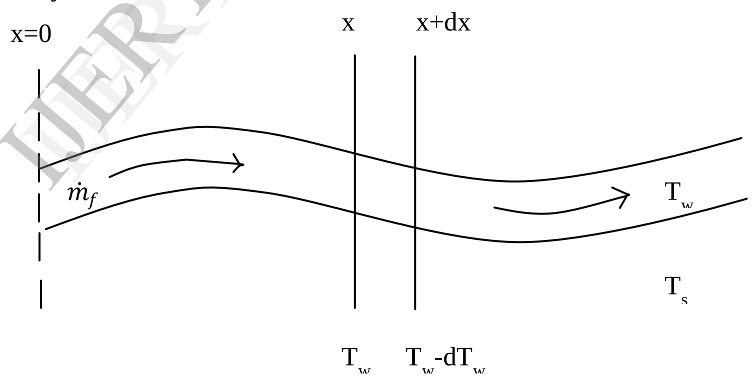

Fig.3 Elemental length 'dx' of heat exchanger integrated with digester.

where,

$$U = \left[\frac{1}{h_w} + \frac{r_1}{K} ln\left(\frac{r_2}{r_1}\right) + \left(\frac{r_1}{r_2}\right)\frac{1}{h_s}\right]^{-1}$$

In order to solve Equation (5), the initial condition namely $T_{w(x=0)} = T_{foN}$ can be used.

Now the solution of Equation (5) is as follows

$T_w(x) = T_s \left\{1 - exp\left(\frac{-2\pi r_1 U x}{\dot{m}_f C_f}\right)\right\} + T_{foN}\ exp\left(\frac{-2\pi r_1 U x}{\dot{m}_f C_f}\right)$(6)Further $T_{w(x=L)} = T_{fi}$(the outlet of heat exchanger will be the inlet to the collectors connected in series and parallel), then one gets.

$$T_{fi} = T_s\left\{1 - exp\left(\frac{-2\pi r_1 Ux}{\dot{m}_f C_f}\right)\right\} + T_{foN}\, exp\left(\frac{-2\pi r_1 Ux}{\dot{m}_f C_f}\right)$$

or,

$$T_{fi} = T_s\{1 - exp(-\varepsilon_1)\} + T_{foN}\, exp(-\varepsilon_1) \quad (7)$$

where,

$$\varepsilon_1 = \frac{-2\pi r_1 U}{\dot{m}_f C_f} L$$

The average water temperature over the length inside heat exchanger has been obtained from Equation (6) as

$$\overline{T_w} = \frac{1}{L}\int_0^L T_w\, dx$$

or,

$$\overline{T_w} = T_s\left\{1 - \frac{1-exp\,(-\varepsilon_1)}{\varepsilon_1}\right\} + T_{foN}\left\{\frac{1-exp\,(-\varepsilon_1)}{\varepsilon_1}\right\} \quad (8)$$

Further, the rate of heat transfer from flowing fluid inside the heat exchanger to the slurry has been obtained as

$$\dot{Q}_{uN} = U2\pi r_1 L(\overline{T}_w - T_s) \quad (9)$$

$$= \dot{m}_f C_f\big(1 - exp(-\varepsilon_1)\big)\big(T_{foN} - T_s\big)$$

Following Tiwari (2002), the outlet fluid temperature at the end of N th collector connected in series can be expressed as follows:

$$T_{foN} = \left(\frac{\dot{q}_{ab}}{U_L} + T_a\right)\left\{1 - exp\left(\frac{-NA_c U_L F'}{\dot{m}_f C_f}\right)\right\} + T_{fi}\, exp\left\{\left(\frac{-NA_c U_L F'}{\dot{m}_f C_f}\right)\right\}$$

Or,

$$T_{foN} = \left(\frac{\dot{q}_{ab}}{U_L} + T_a\right)\{1 - exp(-\varepsilon_2)\} + T_{fi}\, exp(-\varepsilon_2) \quad (10)$$

where,

$$\varepsilon_2 = exp\left(\frac{-NA_c U_L F'}{\dot{m}_f C_f}\right)$$

Now Equation(9) becomes as

$$\dot{Q}_{uN} = \dot{m}_f C_f\big(1 - exp(-\varepsilon_1)\big)\big(T_{foN} - T_s\big)$$

$$= \dot{m}_f C_f\left(\frac{[1 - \exp(-\varepsilon_1)][1 - exp(-\varepsilon_2)]}{[1 - exp\big(-(\varepsilon_1 + \varepsilon_2)\big)]}\right)\left[\frac{\dot{q}_{ab}}{U_L} - (T_s - T_a)\right]$$

$$= \big(\dot{m}_f C_f\big)_{eff}\left[\frac{\dot{q}_{ab}}{U_L} - (T_s - T_a)\right] \quad (11)$$

After substituting above equation in Equation(4), one has

$$M_s C_s \frac{dT_s}{dt} = F_p(\propto AI)_{eff} - (UA)_{eff}(T_s - T_a) + m\big(\dot{m}_f C_f\big)_{eff}\left[\frac{\dot{q}_{ab}}{U_L} - (T_s - T_a)\right]$$

or,

$$M_s C_s \frac{dT_s}{dt} = \left[F_p(\propto AI)_{eff} + \frac{m\big(\dot{m}_f C_f\big)_{eff}\dot{q}_{ab}}{U_L}\right] - \left[(UA)_{eff} + m\big(\dot{m}_f C_f\big)_{eff}\right](T_s - T_a)$$

or,

$$\frac{dT_s}{dt} + aT_s = f(t) \quad (12)$$

where

$$f(t) = \frac{1}{M_s C_s}\left[\left\{F_p(\alpha AI)_{eff} + \frac{\mathrm{m}\big(\dot{m}_f C_f\big)_{eff}}{U_L}\dot{q}_{ab}\right\} + \left\{(UA)_{eff} + m\big(\dot{m}_f C_f\big)_{eff}\right\}T_a\right]$$

and

$$a = \frac{\left\{(UA)_{eff} + m\big(\dot{m}_f C_f\big)_{eff}\right\}}{M_s C_s}$$

The solution of Equation(12) with initial condition i.e. T_s (at t=0) $=T_{so}$ becomes as

$$T_s = \frac{\overline{f(t)}}{a}\{1 - \exp(-at)\} + T_{so}\exp(-at) \quad (13)$$

For a given design and climatic parameters, the hourly slurry temperature (T_s) can be obtained from Equation (13).After hourly variation, the maximum slurry temperature ($T_{s,max}$) for a particular day will be evaluated.

Once, the maximum slurry temperature($T_{s,max}$) is known, the exergy of active bio-gas system can be obtained from the following equation

$$Ex = M_s C_s\left[\{(T_{s,max} - T_{s,initial}\} - (\dot{T}_a + 273)ln\frac{(T_{s,max} + 273}{T_{s,initial} + 273}\right]$$

III. Results and discussion

Design parameters of Table 1 and climatic data of Fig. 4 have been used to evaluate slurry temperature by using Equation(13). The hourly variation of slurry temperature for different configuration of flat plate collectors (FPC's) has been shown in Fig. 5. It is clear that maximum slurry temperature for all FPC's connected in series (m=1 and

N=40) is about 15^0C. This is not the optimum temperature (~ 37^0C) for biogas production. Hence the hourly slurry temperature has been calculated for other configuration as (m=2 and N=20; m=4 and N=10; m=5 and N=8; m=8 and N=5). The results have also been shown in Fig.(6-9). It is seen from Fig 5 that the optimum slurry temperature is achieved for configuration of m=5 and N=8. This can be possible because of less thermal energy loss for 8 flat plate collectors are connected in series (N=8). In other combination thermal losses are significant.

Table 1:Design parameters of active biogas plant

Parameters	**Values**	**Parameters**	**Values**
A_c	2 m^2	M_s	2500 kg
C_s	4190 J/kg K	K	204 W/mK
U_{L1}	3.56 W/ m^2 ^0C	F_{RC}	0.95
h_{bf}	100 W/m^{2} ^0C	U_{LC}	6 W/m^{2} ^0C
$U_{tc,a}$	9.5 W/m^{2} ^0C	L	25 m
r_1	0.0125 m	A_s	8.5 m^2
r_2	0.0175 m	N	40
r_3	0.625 m	h_c	58 W/m^{2} ^0C
A_v	10.3 m^2	h_{rps}	5.2W/m^{2} ^0C
A_h	8.5 m^2	h_{sa}	2.8 W/m^{2} ^0C
A_v'	4.5 m^2	h_1	0.66 W/m^2
A_h'	0.9 m^2	h_2	5 W/m^2
h_3	1.32 W/m^2	h_4	0.78 W/m^2

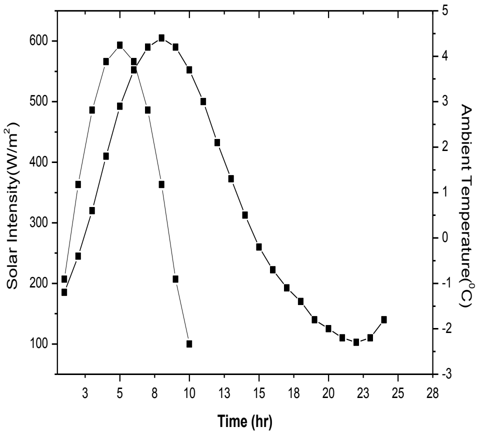

Fig 4. Hourly variation of I(t) and Ta for typical day of Srinagar.

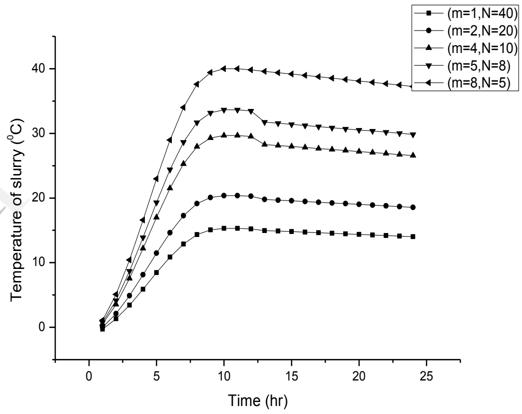

Fig.5. Hourly slurry temperature for different configurations.

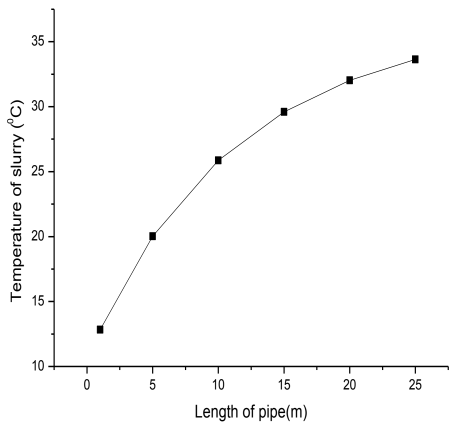

Fig 6. Effect of length on $T_{s,max}$.

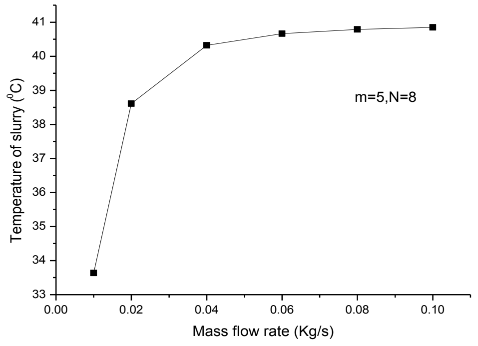

Fig 7. Effect of mass flow rate on $T_{s,max}$.

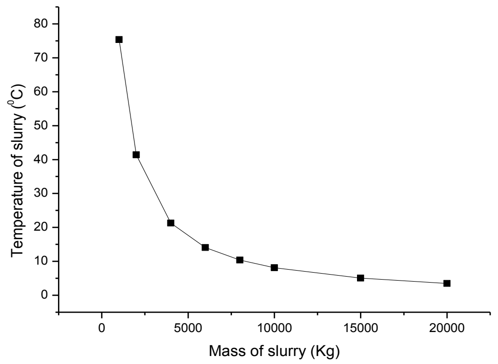

Fig 8. Effect of mass on $T_{s,max}$.

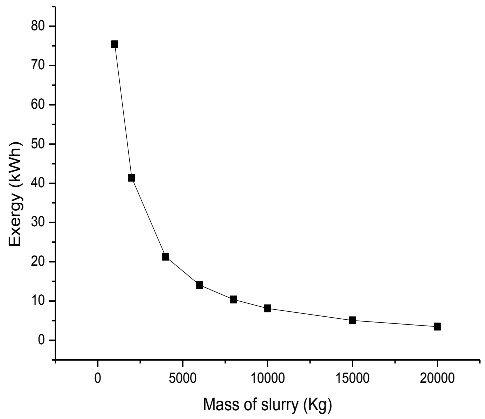

Fig 9. Effect of exergy with mass of slurry.

For the optimized number of flat plate collectors in series and parallel (m=5, parallel and N=8, series), parametric studies have been carried out. Fig. 6 shows the effect of heat exchanger length on maximum slurry temperature ($T_{s,max}$) and it can be seen that the variation of maximum slurry temperature ($T_{s,max}$) becomes insignificant after 25 m length of heat exchanger. It is not economical to have more length of heat exchanger due to copper materials.

Effect of mass flow rate of fluid on maximum slurry temperature ($T_{s,max}$) for other optimized parameters namely configuration and length of heat exchanger has been shown in Fig.7. It can be seen that there is not much variation in maximum slurry temperature ($T_{s,max}$) after mass flow rate of 0.04 kg/s. Hence the mass flow rate of 0.04 kg/s is optimum for a given other design parameters.

In Fig. 8, the variation of maximum slurry temperature ($T_{s,max}$) with different mass of slurry has been shown. The figure indicates that the slurry temperature is maximum at lower value of slurry mass which is not suitable for biogas production. The optimum temperature can be achieved at the mass of 2500 kg.

Equation (13) has been used to evaluate exergy of active biogas plant for different mass of slurry. The results have been shown in Fig. 9. The exergy of active biogas plant at optimum parameters is 40 kWh.

IV. REFERENCES

1. Bundit Limmeechokchai, and Saichit Chawana, “The case of the improved cooking stove and the small biogas digester”, Sustainable energy development strategies in the rural Thailand,Renewable and Sustainable Energy Reviews, Volume 11, Issue 5, pp. 818-837, June 2007.
2. Matthew Landi, Benjamin K. Sovacool, and Jay Eidsness, “Cooking with gas: Policy lessons from Rwanda's National Domestic Biogas Program (NDBP)”, Energy for Sustainable Development, Volume 17, Issue 4, pp 347-35, August 2013.
3. Ershad Ullah Khan, Brijesh Mainali, Andrew Martin, and Semida Silveira, “Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study”, Sustainable Energy Technologies and Assessments, Volume 7, pp 68-78, September 2014.
4. Karthik Rajendran, Solmaz Aslanzadeh, Fredrik Johansson, and Mohammad J. Taherzadeh,“Experimental and economical evaluation of a novel biogas digester”,Energy Conversion and Management, Volume 74, Pages 183-191, October 2013.
5. Vianney Tumwesige, David Fulford, and Grant C. Davidson, “Biogas appliances in Sub-Sahara Africa, Biomass and Bioenergy”, In Press, Corrected Proof, Available online 15 March 2014.
6. Tushar Jash, and Sujay Basu, “Development of a mini-biogas digester for lighting in India”, Energy, Volume 24, Issue 5, pp 409-411, May 1999.
7. Li Yingjian, Qiu Qi, He Xiangzhu, Li Jiezhi, andEnergy balance and efficiency analysis for power generation in internal combustion engine sets using biogas,Sustainable Energy Technologies and Assessments, Volume 6, Pages 25-33, June 2014.
8. A. González-González, M. Collares-Pereira, F. Cuadros, and T. Fartaria, “Energy self-sufficiency through hybridization of biogas and photovoltaic solar energy: an application for an Iberian pig slaughterhouse”, Journal of Cleaner Production, Volume 65, pp 318-323, 15 February 2014.
9. Abdullah Akbulut, “Techno-economic analysis of electricity and heat generation from farm-scale biogas plant: Çiçekdağı case study”,Energy, Volume 44, Issue 1, pp 381-390, August 2012.
10. C.X. Cáceres, R.E. Cáceres, D. Hein, M.G. Molina, and J.M. Pia, “Biogas production from grape pomace: Thermodynamic model of the process and dynamic model of the power generation system”, International Journal of Hydrogen Energy, Volume 37, Issue 13, pp 10111-10117, July 2012.
11. G.N. Tiwari, A. Chandra, K.K. Singh, S. Sucheta, and Y.P. Yadav, “Studies of KVIC biogas system coupled with flat plate collector”, Energy Conversion and Management, Volume 29, Issue 4, pp 253-257, 1989.
12. G.N. Tiwari, S.K. Singh, and Kailash Thakur, “Design criteria for an active biogas plant”, Energy, Volume 17, Issue 10, pp 955-958, October 1992.

13. R.A. Gupta, S.N. Rai, and G.N. Tiwari, An improved solar assisted biogas plant (fixed dome type): A transient analysisEnergy Conversion and Management, Volume 28, Issue 1, pp 53-57, 1988.
14. Su Yuan, Tian Rui, and Yang Xiao Hong, "Research and analysis of Solar Heating Biogas Fermentation Systems", Procedia Environmental Sciences, Volume 11, pp 1386-1391, 2011.
15. Feiqing Dong,and Jianbo Lu, "Using solar energy to enhance biogas production from livestock residue- A case study of the Tongren biogas engineering pig farm in South China", Energy, Vol.57, pp 759-765,2013.

Nomenclature

A Area (m^2)
A_h Horizontal area of the gas holder exposed to solar radiation (m^2)
A_v Vertical area of the gas holder which is exposed to solar radiation (m^2)
A_t Area of the top (m^2)
$A_{h'}$ Slurry vertical area (m^2)
$A_{v'}$ Vertical area of the gas holder which is submerged in the slurry (m^2)
A_c Area of flat plate collector (m^2)
C_f Specific heat capacity of fluid (Anti-freeze liquid) (J/kg^o C)
C_s Specific heat capacity of slurry (J/kg^o C)
dxElemental section
Ex Exergy (W)
FPC Flat plate collector
F_R Flow rate factor (dimensionless)
h Heat transfer coefficient (W/m^{20}C)
h_{rps} Radiative heat transfer coefficient (W/m^{20}C)
h_1 Heat transfer coefficient from gas holder plate to gas (W/m^{20}C)
h_2 Convective heat transfer coefficient from gas holder plate to ambient (W/$m^{2\,0}$C)
h_3 Heat transfer coefficient from gas to slurry (W/m^{20}C)
h_4 Heat transfer coefficient from slurry to ground (W/m^{20}C)
h_c Heat transfer coefficient from gas holder to slurry (W/m^{20}C)
h_s Heat transfer coefficient inside the tube from tube to slurry (W/m^{20}C)
h_w Heat transfer coefficient inside the tube from water to tube (W/m^{20}C)
h_{sa} Heat transfer coefficient from slurry to air (W/m^{20}C)
I (t) Incident solar intensity (W/m^2)
K Thermal conductivity (W/m K)
$\dot{m}_f$ Mass flow rate of flowing fluid (kg/sec)
M_S Mass of slurry (kg)
N Number of photovoltaic thermal flat plate collector connected in series
N_o Number of sunshine hours (hr)
$\dot{Q}_{u,N}$ Rate of useful thermal energy transfer (kW)
r_1 Inner radii of the tube (m)
r_2 Outer radii of the tube (m)
t Time (sec)
T Temperature (^{0}C)
T_a Ambient temperature (^{0}C)
T_{foN} Outlet temperature of fluid of the N^{th} photovoltaic thermal flat plate collector (^{0}C)
T_{fi} Inlet temperature of fluid in the photovoltaic thermal flat plate collector (^{0}C)
T_g Gas holder temperature (^{0}C)
T_p Plate temperature (^{0}C)
T_s Slurry temperature (^{0}C)
T_w Fluid temperature (^{0}C)
U Overall heat transfer coefficient for the system (W/m^{20}C)
$\propto'$ Absorptivity of dome

Subscripts

a Ambient air
eff Effective
ele Electrical
g Glass
s Slurry
w Water

Greek letters

α Absorptivity of solar cell
α' Absorptivity of dome
$(\alpha\tau)_{eff}$ Product of effective absorptivity and Transmissivity
τ Transmissivity
η_m Module efficiency