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Thermal Simulation of Biogas Plants Using Mat Lab

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ABSTRACT
The major prerequisite for the optimum production of methane from a biogas plant is the sustenance of digester temperature within the narrow limits (30^0C-35^0C). It is experimentally investigated that, the MIT biogas plant is not maintaining optimum temperature, this decreases the efficiency and increases the detention time for charge. To maintain the plant in optimum temperature, it is necessary to find out the heat losses from the biogas plant and the external energy inputs need to operate the plant. Rate of gas yield, and the detention time (time necessary to anaerobically digest organic wastes) in a biogas reactor, are favorable functions of the temperature in the digester. A thermal simulation for MIT biogas plant has developed using matlab in order to understand the heat transfer from the slurry and the gas holder to the surrounding earth and air respectively. The computation has been performed when the slurry is maintained at 20^0C and 30^0C, optimum temperature of anaerobic fermentation. If the slurry is considered to be at 35^0C, the optimum temperature of anaerobic fermentation, the total heat loss from the plant is higher than the heat loss when the slurry is maintained at 20^0C. The heat calculations provide an appraisal for the heat which has to be supplied by external means to compensate for the net heat losses which occur if the slurry is to be maintained at 35^0C. A solar system with auxiliary electric heater is designed for maintaining the slurry at 35^0C.In conclusion; the results of thermal analysis are used to define a strategy for operating biogas plant at optimum temperatures. .
Keywords-Anaerobic fermentation, Biogas plant, Digester, Detention time, Heat loss, Slurry, Solar system, Thermal simulation, MIT, Matlab

I. Introduction

Biogas is produced by anaerobic digestion with anaerobic bacteria or fermentation of biodegradable materials such as manure, sewage, municipal waste, green waste, plant material, and crops. It is primarily methane (CH_4) and carbon dioxide (CO_2) and may have small amounts of hydrogen sulphide (H_2S), moisture and siloxanes. Growth of micro-organisms in the anaerobic digester improves in two distinct temperature, mesophilic (28^0C-42^0C) and thermophilic(45^0C-65^0C)[1].Due to free ammonia inhibition, under mesophilic range methane production is 25% higher than under thermophilic range[2].Maximum methane production occurred in the mesophilic range rather than thermophilic range[3].There is no significant effect of temperature (33^0C vs 55^0C) on methane production[4].Optimum production of methane is the sustenance of digester temperature at 35^0C[5].

To develop a reliable thermal simulation for MIT biogas plant to maintain it in optimum temperature, which helps to increase gas yield, as well as reducing detention time for charge [6]. Result of thermal analysis will define a strategy for operating biogas plants at optimum temperature. A thermal model for the biogas plant has been developed mainly for predicting the diurnal variation of temperature of gas holder, which is exposed to the atmosphere and the slurry which is enclosed in the digester pit. Thermal analysis has been performed for two conditions, when slurry is maintained at ambient temperature of 20°C and 35°C, optimum temperature of anaerobic fermentation [7]. Once the temperatures are calculated, heat loss and external energy needed to operate the plant at any desired temperature can be found.

II. Thermal simulation

Rate of gas yield and detention time are favorable function of the temperature in the digester. A thermal model is needed in order to understand heat transfer from gas holder and slurry to the air and surrounding earth respectively. The calculation provides an appraisal of the heat which has to supply externally to compensate net heat loss while maintaining slurry at 35°C.

2.1 Assumption

- Gas holder is isothermal
- Gas within the drum is isothermal
- Slurry is isothermal
- Ambient air is isothermal
- Earth Surrounding the digester well is isothermal

2.2 Energy conservation relation for gas holder

Energy conservation relation for gas holder is:

$$(m\,c_p)_D \frac{dTd}{dt} = [I\,\alpha\,A_T + I\,\alpha\,A_S] + \sigma\,\varepsilon\,A_T(T_{SKY}^4 - T_D^4) + \sigma\,\varepsilon\,\frac{As}{2}(T_{SKY}^4 + T_{GR}^4 - 2T_D^4) + \sigma\,\varepsilon\,A_T(T_S^4 - T_D^4) - h_1 A_T(T_D - T_A) - h_2 A_S(T_D - T_A) - h_3(A_T + A_S)(T_D - T_G) - h_4 A_S(T_D - T_S) \quad (1)$$

Left term is the energy storage in the gas holder, First term on the right is the solar influx, Second is the irradiative exchange of the roof of gas holder with sky, the third is the irradiative exchange of the outer side surface of gas holder with the sky and ground, the fourth is the irradiative exchange of the inside of the drum with slurry. The negative terms represent convective exchange, the first bracketed term shows the heat lost by convection to air from the outside surface of the gas holder, the second shows the heat lost to gas inside the gas holder and the last term shows the heat lost to slurry through the skirt of the gas holder that is immersed inside the slurry. Since the gas holder rides up and down depending on gas accumulated inside it, it has been assumed, for convenience, that the gasholder is always half full (i.e., half the height is exposed to atmosphere, while the bottom half is immersed inside the slurry).

2.3 Energy conservation relation for slurry

$$(m\,c_p)_S \frac{dTS}{dt} = \sigma\,\varepsilon\,A_T(T_D^4 - T_S^4) + h_4 A_S(T_D - T_S) + h_5 A_T(T_G - T_S) - h_6 A_W(T_S - T_\infty) \quad (2)$$

Last term on the right is the heat lost from slurry through the side walls of the digester pit.

2.4 Energy conservation relation for gas

$$h_3(A_T + A_S)(T_D - T_G) = h_5 A_T(T_G - T_S) \quad (3)$$

By solving,

$$T_G = a\,T_D + b\,T_S \quad (4)$$

2.5 Computational Program for Thermal Simulation

```
functionxdot = thermal(t,x)
% Thermal analysis of biogas plant
TD = x(1);
TS = x(2);
TG = x(3);
% Provide parameters here
I = solar irradiance value; % J/(m2 .s)
α= 0.9;
At = 2.293;   % m2
As = 8.57;   % m2
σ= 5.678e-08;  % W/ m2.K4
ε = 0.9;
TA = --+273;    % K
TSKY=  --+273; % K
TGr=  --+273; % K
h1 = 28.706;   % W/ m2.K
h2 = 9.576; % W/ m2.K
h3 = 4.091;  % W/ m2.K
h4 = 1.57; % W/ m2.K
mD = 1188; % kg
cpD = 0.49e+03; % J/kg.K
mS = 15000; % kg
cpS = 4.2e+03;  % J/kg.K
```

Coefficients	Description	Value of coefficient – (w /m²k)
h_1	Top horizontal of gas holder to air.	28.7
h_2	Gas holder side surface to air	9.58
h_3	Gas holder inner surface inner surface to gas	4.09
h_4	Gas to slurry	4.09
h_5	Gas holder to slurry	4.09
h_6	Overall heat transfer co-efficient for transfer from slurry to ground $[1/h'_6 + l_1/k_1 + l_2/k_2 + l_3/k_3]^{-1}$ h'_6=50 (taking the slurry properties as that of water) l_1=.024,l_2=.23,l_3=.25-m k_1=.26,2=k_2.16,k_3=.48— (kcal/mhr^{0}k) refer to stone masonry	1.571
α	Absorption coefficient of gas holder for solar radiation	0.9

```
h5 = 4.091; %W/ m2.K
h6 = 1.57; % W/ m2.K
Aw = 33.43; % m2
T∞ = --+273; % K
a = 0.7;
b = 0.3;
% Here are the Governing Equations
% Energy Conservation for Gas Holder
dTDdt = (((I×α×At)+(I×α×As)) + σ×ε×(At×(Tsky4 - TD4)+ (0.5×As)×(Tsky4 + TGr4 - 2×(TD4))) + σ×ε×At×(TS4 - TD4).- (h1×At×(TD - TA) + h2×As×(TD - TA)) - (h3×(At+As)×(TD - TG)) - h4×As×(TD-TS))/(mD×cpD);
% Energy Conservation for  Slurry
dTSdt = (σ×ε×(TD4 - TS4)×At + h4×As×(TD - TS) + h5×At×(TG - TS) - h6×Aw×(TS - T∞))/(mS×cpS);
% Energy Conservation for  gas
dTGdt = a×dTDdt + b×dTSdt;
xdot = [dTDdt; dTSdt; dTGdt];
```

In the computational program, solar radiation, ambient temperature, sky temperature which are function of time't' have to be supplied.

The temperatures T_D, T_G and T_S are constrained to return to their starting values at the end of a 24-hr period. This is equivalent to,

$$\int_0^{24\ hr}(\text{Rate of heat input})dt = \int_0^{24\ hr}(\text{Rate of heat in gas holder} + \text{slurry})dt + \int(\text{Rate of heat loss})dt \quad (5)$$

The computations were carried on mathematical solver –mat lab and involved iterations until the initial values of T_D and T_S agreed with the final values of T_D and T_S after one 24-hr period.

Table 1 General Coefficients for convective and radiative heat transfer

2.6 Soil Temperature

1. When the depth is 0-cm

Tsoil= 4.593 +1.015×Tair− 0.016×longitude − 0.029× latitude (6)

2. When the depth is 20-cm

Tsoil= 13.65 + 0.781×Tair− 0.036×longitude − 0.134×latitude (7)

3. When the depth is 40-cm

Tsoil= 15.73+ 0.739×Tair− 0.046×longitude −0.143×latitude − 0.001× altitude (8)

Pune is located in longitude 73°51’19’’ E, latitude 18°51’19’’N and altitude is 562m.

2.7 Hourly solar radiation data

Hourly solar radiation data supplied from, rredc.nrel.gov/solar/new/-data/India/nearest cell.new.cgi[9] by knowing latitude and longitude of the interested area.

III. Experimental and computational validation

First computationally, find out that what is the variation of gas holder temperature when slurry is at 20°C with respect to ambient condition, then it is validated with experimental measured value, if it agrees, this shows that chosen value for heat transfer co-efficient represent the real system. Again, gas holder temperature calculated computationally when slurry is at 35°C.Once the temperature are calculated, heat loss from the biogas plant and external energy input necessary to operate the plant at any desired temperature can be find out.

3.1 Gas holder temperature (computational, experimental) when slurry temperature maintained at 20^0C

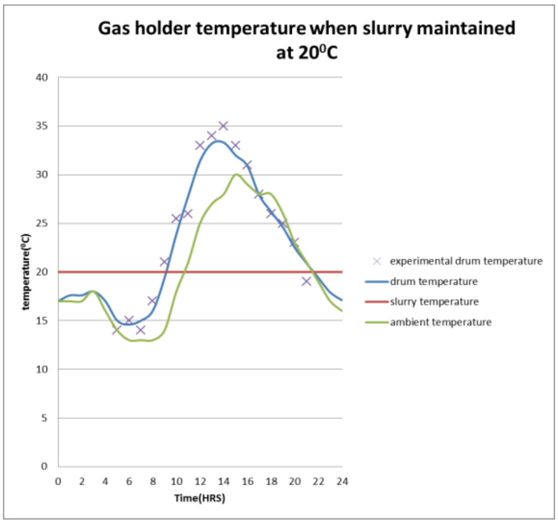

Figure 1 Gas holder temperature when slurry temperature maintained at 20^0C

Result shows that experimentally measured value of gas holder which agrees quite well with computed value, this shows that chosen value for heat transfer co-efficient represent the real system.

3.2 Computational gas holder temperature when slurry temperature maintained at 35^0c

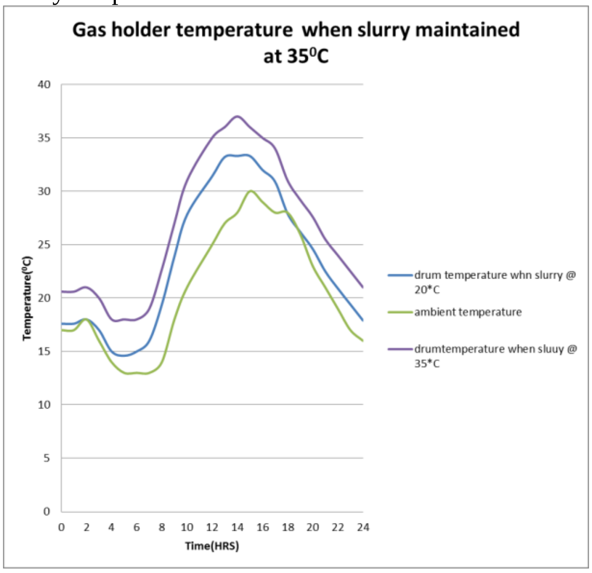

Figure 2 Gas holder temperatures when slurry temperature maintained at 35^0C

By knowing gas holder temperature, heat loss from the biogas plant and external energy input necessary to operate the plant at any desired temperature can be found.

IV. Heat Loss from Biogas plant

Heat Loss through Radiation from Roof

$Q=\sigma \times\varepsilon \times A_t[(T_D^4 - T_{sky}^4) + (T_D^4 - T_{slurry}^4)]$ (9)

Heat Loss through Radiation from Side

$Q= \sigma \times \varepsilon \times A_S/2\times (2T_D^4 - T_{Sky}^4 - T_{ground}^4)$ (10)

Heat Loss through Convection from Roof

Q= [h $_1$ A_t (T_D – T_A) + h_3 A_t (T_D – T_G)] (11)

Time--hrs	Heat loss through radiation from roof	Heat loss through convection from roof	Heat loss through radiation from side	Heat loss through convection from side
1	140.23	117.8	-18.25	-343.9
2	140.2	117.8	-18.25	-343.9
3	157.83	-20.31	-28.83	-434.3
4	113.96	206.5	-38.97	-356
5	27.54	186.2	-201.9	-790.31
6	10.47	324.31	-192.5	-699.9
7	27.54	423.15	-132.36	-494.87
8	70.53	670.3	19	17.72
9	220	1273.5	476	1465.1
10	421.61	1437.66	915.95	2589.9
11	607.62	1690.52	1349.81	3702.76
12	785.74	1632.3	1671.14	4366.3
13	871.37	1595.75	1830.04	4682.73
14	878.03	1390.9	1773.1	4453.93
15	870.2	899.7	1596.9	3827.16
16	752.12	560.9	1262.04	2928.3
17	603.9	56.51	820.38	1685.94
18	517.7	-363.58	530.38	814.54
19	441.71	-285.04	423.1	585.3
20	343.81	-93.1	312.06	395.15
21	270.58	-14.56	206.07	165.9
22	202.59	88.7	116.87	-12.1
23	136.41	191.94	28.23	-190.1
24	97.05	231.21	-23.58	-304.75
total	8708.97-KJ/day	12319.2-KJ/day	12676.93-KJ/day	27710.6-KJ/day

Heat Loss through Convection from Side

Q= [h_2A_S (T_D – T_A) + h_3 A_S (T_D – T_G) + h_4 A_S (T_D – T_S)] (12)

Slurry Cooling Heat Loss

Q= m×C_p×(T_2–T_1) (13)

Slurry to Ground Heat Loss

Q= h_6 A_W (T_S – T_∞) (14)

V. Results and discussions

After the temperatures were calculated, the heat loss from the gas holder and slurry were calculated. Results are tabulated in Table-2 and Table-3

Table-2 Result of Computations of Heat Losses when Slurry is at 20^0C.

Slurry to ground heat loss= -24805.67(gain)
Charge cooling loss= Nil
Total heat loss=36610-KJ/day

Table-3 Result of Computations of Heat Losses when Slurry is at 35^0C.

Time--hrs	Heat loss through radiation from roof	Heat loss through convection from roof	Heat loss through radiation from side	Heat loss through convection from side
1	-400.83	805.7	517	-1858.3
2	-410	756.3	485	-1960.8
3	-386.9	642.87	492.6	-2000
4	-433	869.6	477.12	-1921.7
5	-496.66	997.64	397.4	-2048.46
6	-537.11	1012.2	326.5	-2214.35
7	-505.7	1185.2	435.6	-1855.5
8	-207.84	2766.7	1470.5	1425.1
9	223.1	4654.9	2900.4	5537.9
10	744.18	6062.06	4430.3	9241.1
11	1180.16	7172.4	5729.3	12132.6
12	1505.9	7509.5	6559.7	13616.3
13	1603.41	7408.7	6741.8	13800
14	1486.7	6724.53	6253.5	12576.2
15	1245.95	5304.2	5248.97	10022.1
16	810.3	3739.68	3810.53	6580.7
17	331.3	1844.05	2222.3	2452.5
18	45.4	482.46	1226.9	-371
19	-70.5	383.1	984.02	-980
20	-178.9	545.37	841.1	-1221.8
21	-255.64	623.91	726.6	-1451.1
22	-331.13	702.4	613.3	-1680.3
23	-396.21	830.41	533.1	-1807
24	-442.15	820.25	445.3	-2024.2

total	4123.92 —KJ/day	63844.13— KJ/day	52641.9 — KJ/day	63990 — KJ/day

Slurry to ground heat loss= 62018.3-KJ/day
Charge cooling loss= 62760 -KJ/day
Total heat loss=309378-KJ/day
5.1 External energy
Relatively high cost of fossil fuels and low cost of solar collectors support the idea of using solar energy as a heating means of digester
Total heat loss from plant=309378-KJ/day
Solar influx=144413-KJ/day
Net heat loss=164965-KJ/day
m'cp (T_O-T_i) =1.909KJ/s

C_p –of water-4.184-KJ/kg k
T_O –out let temperature of solar collector-60 ^{0}C
T_i--inlet temperature of solar collector-20^{0}C
m'=.0114-Kg/s
Electric heater is needed when sufficient solar influx unavailable.
P=1.909×10^3—J/s (W)

VI. Conclusion

Optimum temperature for the anaerobic fermentation is within the narrow limits (30°C-35°C).For maintaining the biogas plant at 35°C a computational program in matlab has been developed. Gas holder temperature were calculated ,experimentally and computationally when slurry is maintained at 20°C.Result shows computational value matches with experimental value, that means chosen value of heat transfer co-efficient represent real system. Again, gas holder temperature calculated computationally when slurry is at 35°C.Heat loss from the biogas plant has calculated at 20°C & 35°C, and tabulated. Energy required to charge daily kitchen waste from 20°C to 35°C has considered. For external heat supply a solar water heater system with auxiliary heater is designed. Experimental results in the month of January shows, average generated gas is 12.9 m³/day only (rated 45-50 m^3/day), this is because of plant is not maintaining optimum temperature for anaerobic fermentation and average feeding is 120 kg/day instead of 500 kg/day. In conclusion, the result of thermal analysis is used to define a strategy for operating biogas plant at optimum temperatures.

List of symbols

A_s-half of the area of the skirt of gas holder
A_t-area of the top surface of gas holder
A_w-circumferential area of the slurry pit
a, b-constants
C_p-specific heat
h_1-h_5- convective heat transfer coefficients

T- temperature.
t-time
α - absorptivity's at short wavelengths (for solar incidence)
ε -emissivity's at long wavelengths
σ -Stefan-Boltzmann constant
m_D – Mass of the gas holder
m_S – Mass of the slurry
C_{pD}-Heat capacity of gas holder
C_{pS}-Heat capacity of Slurry

Subscripts

A- Ambient
D- Gas holder drum
G- Gas inside the drum
S-slurry
∞-soil under the surface

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