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Transient Analysis of a Biogas System Integrated with a Solar Water Heater

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ABSTRACT

A transient analysis of Khadi and Village Industries Commission (KVIC) design of biogas integrated with a solar water heater is presented. In order to reduce the night heat losses from the top of the water heater which is installed over the dome of a biogas plant, movable insulation was used during off-sunshine hours, and the effect of this insulation has been studied. The analysis indicates that the quasi-steady state of the biogas plant is reached only 7-10 days after feeding the slurry into the digester.

INTRODUCTION

Prasad and Sathyanarayan's analysis of a Khadi and Village Industries Commission biogas plant (KVIC model)[1] assumes that the system is in quasi-steady state condition. Basically a KVIC biogas plant consists of a digester and a floating gas holder (Fig. 1). The digester is a permanent cylindrical structure in the ground, made up of concrete, brick/cement, or any insulating material to reduce the side losses to the ground. It is designed so that slurry can be fed into the digester, and is provided with an outlet for the slurry with a partition wall. The level of the inlet for the slurry is just above the outlet so that the used slurry will be replaced automatically. Unlike the Chinese model, it has a floating gas holder made up of any conductive and rigid material which floats inside the digester, as shown in Fig. 1. A gas outlet is provided by means of a gate valve in the gas holder. Sometimes this device is referred to as a conventional biogas plant.

During operation, the slurry is fed into the digester, and it takes about 20-24 days to reach the optimum temperature for fermentation to take place and the production of biogas to start. This condition is known as the quasi-steady state condition. In order to reduce the time for anaerobic fermentation to take place and for a higher slurry temperature to be reached, Reddy *et al.*[2] have integrated a biogas plant with a solar water heater and a solar still in their analysis. In this case, a solar water heater (like Fig. 1b) or a solar still was constructed over the floating gas holder or dome to enhance solar flux during sunshine hours and to reduce night heat losses from the top, which account for about 60% of the total heat losses from a biogas plant. They observed that there is an appreciable reduction of heat losses from the top of the biogas plant. In addition to this, the hot water obtained from the water heater/solar still can be used for making the daily charge, i.e. for 'hot-charging' the plant. The other option for increasing the slurry temperature is to use a greenhouse structure over the dome of the plant (Bansal *et al.*[3,4] and Kalia[4,5]).

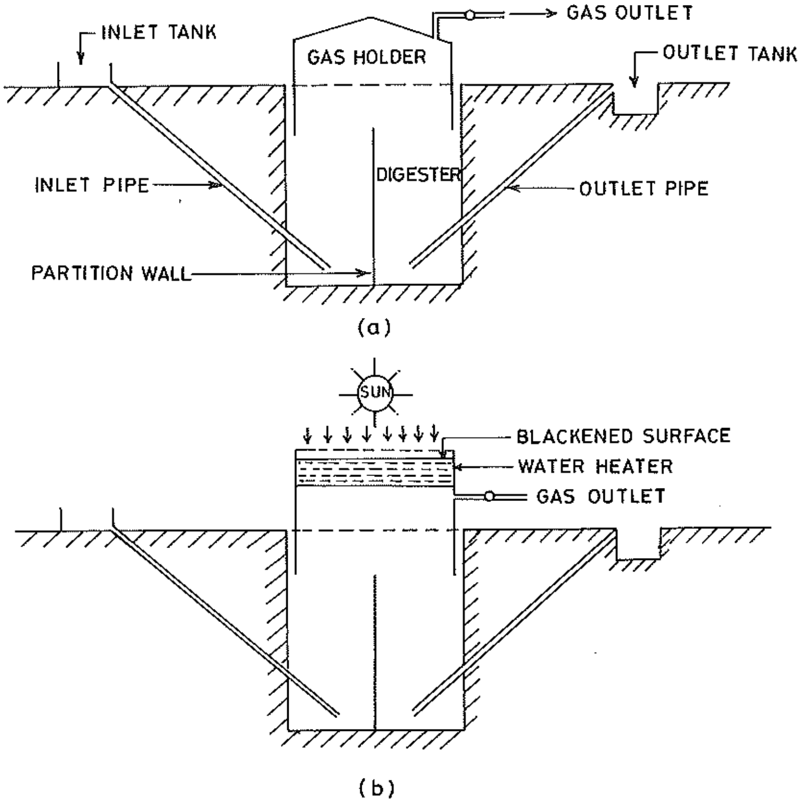

Fig. 1 (a) Khadi Village and Industries Commission (KVIC) biogas plant.
(b) Proposed KVIC integrated water heater biogas plant.

Bansal *et al.*[4] have used locally available PVC plastic film of 25 μm thickness for the construction of a greenhouse with an iron structure to sustain the upthrust due to heavy dust storms during summertime. The greenhouses were erected over the dome of two biogas systems of 85 m^3 and 8 m^3 capacity, situated at Masoodput (a village near Delhi). They observed an increase of 15-20% in the production of biogas. Later on Sant Ram *et al.*[6] studied the effect of a shallow solar pond (SSP) water heater integrated with the dome of the plant on the temperature of the gas holder, gas, slurry, etc. It was observed that (i) the system is capable of providing hot water up to a temperature of 40°C during the noon period, which in turn can be used for hot-charging the slurry and to reduce the heat losses from the slurry, and (ii) there is an increase in the temperature of the slurry from 20 to 27°C.

Recently, Tiwari and Chandra[6] have pointed out some difficulties during the operation of the system proposed by Sant Ram *et al.*,[5] notably concerning bulging in the SSP water heater, a sealing problem, significant heat losses from the top during the night, and maintenance problems. Consequently they recommend the use of a built-in-storage water heater and the use of movable insulation during off-sunshine hours. The use of movable insulation during off-sunshine hours also reduces the night heat losses from the water heater, and the water heater retains a temperature of up to 35°C the following morning. This effect has not been noted by Sant Ram *et al.*[5]

It can be shown experimentally that anaerobic fermentation in a biogas plant only takes place after 20-24 days of feeding slurry into the digester. But this period is highly dependent on both the climatic conditions and the system parameters. Consequently it is essential to propose a theory which can predict the behaviour of a biogas plant between the time the slurry is fed into it and the beginning of anaerobic fermentation, and this behaviour has not in fact been studied to date. The studies have all been done with the assumption that the system is in a quasi-steady state, but in the case of a solar-assisted biogas plant, in addition to an increase in the slurry temperature, anaerobic fermentation takes place a good deal before it does in the conventional system, and this too is an important parameter. This behavior cannot be studied without knowing the transient behaviour of the system.

The intention of this study is to present a transient analysis of a KVIC biogas plant integrated with a built-in-storage water heater (Fig. 1b). In this analysis, the amount of heat lost to the ground through the basement of the digester has been taken into account, as it was by Prasad and Sathyanarayan,[1] which helps in analysing the system under transient conditions and also predicts an aerobic fermentation period. The time for anaerobic fermentation in a solar-assisted biogas plant is significantly reduced as compared to the time required in a conventional system. An analytical expression for the water temperature, the gas holder, the gas temperature, and the slurry temperature has been derived to predict their transient behaviour before reaching a quasi-steady state condition both for the conventional and for the proposed biogas plant.

ANALYSIS

In writing an energy balance equation for various components of biogas plants, the following assumptions have been made – in addition to those made by Tiwari and Chandra.[6]

a) The heat capacity of the gas holder and the gas inside the holder are negligible.

b) The heat lost through evaporation from the slurry to the ambient air around the gas holder is negligible.

c) There is no stratification in the water and gas column in the gas holder.

d) The steady-state heat transfer from the slurry to the ground has been taken into consideration.

Following Tiwari and Chandra,[6] the energy balance for the absorbing plate, the water mass, the gas and the slurry can be written as:

(i) Absorbing plate:

$$\alpha\tau S(t) = h_o\,(T_b - T_w) + h_o'\,(t)\,(T_b - T_a). \tag{1}$$

(ii) Water mass:

$$M_w C_w \frac{dT_w}{dt} = A_o h_o\,(T_b - T_w) - h_2 A_h\,(T_w - T_p) - \dot{m} C_w x\,(T_w - T_{in}). \tag{2}$$

(iii) Gas holder:

$$h_2 A_h (T_w - T_p) + \frac{A_v}{2} \cdot \alpha' S_v = h_1 A_t (T_p - T_g) + h_{rps} (T_p - T_s) A_h$$

$$+ A_v' h_c (T_b - T_s) + A_v h_{pa} (t) (T_p - T_a). \qquad (3)$$

(iv) Gas:

$$h_1 A_t (T_p - T_g) = h_3 A_h (T_g - T_a). \qquad (4)$$

(v) Slurry:

$$M_s C_s \frac{dT_s}{dt} = h_3 A_h (T_g - T_s) + h_{rps} (T_p - T_s) A_n + A_v' h_c (T_p - T_s) - h_4 A_o (R_s - T_\infty), (5)$$

where $h_o'(t)$ and $h_{pa}(t)$ are a time-dependent heat transfer coefficient having one value during sunshine hours and another during off-sunshine hours when the system is covered with movable insulation to avoid night heat losses from the top of the collector and sides of the dome so that:

$$h_4' = [\frac{L_1}{K_1} + \frac{L_2}{K_2}]^{-1}.$$

After eliminating T_b, T_p and T_g from Eqs. (1), (3) and (4), Eqs. (2) and (5) can be written as:

$$\frac{dT_w}{dt} + a_1 T_w + b_1 T_s = g(t), \qquad (6)$$

and

$$\frac{dT_s}{dt} + a_2 T_w + b_2 T_s = f(t), \qquad (7)$$

where a_1, a_2, b_1 and b_2 are constants, depending on the system and the various heat transfer coefficients, while $g(t)$ and $f(t)$ are time-dependent constants, depending on climatic conditions, system parameters, and various heat transfer coefficients as well.

Equations (6) and (7) can be solved by using the initial boundary conditions, viz., $T_w = T_{wo}$ and $T_s = T_{so}$ at $t = 0$. After determining T_w and T_s, the temperature of the gas holder and of the gas can be determined from Eqs. (3) and (4) respectively. During off-sunshine hours, $S = S_v = 0$ and the numerical values of h_o (t) and h_{po} (t) will change.

NUMERICAL RESULTS AND DISCUSSION

In order to appreciate the results of integrating a biogas plant with a solar water heater, numerical calculations have been made for the following set of parameters (Sant Ram *et al.*[5]).

h_o = 2780 W/m² °C $\qquad$ M_s = 20 000 kg

$h_o' = 5.43\ \text{W/m}^2\ ^\circ\text{C}$, during day

$\quad = 0.8\ \text{W/m}^2\ ^\circ\text{C}$, during night

$h_1 = 0.66\ \text{W/m}^2\ ^\circ\text{C}$

$h_2 = 135\ \text{W/m}^2\ ^\circ\text{C}$

$h_3 = 1.32\ \text{W/m}^2\ ^\circ\text{C}$

$h_4 = 0.6\ \text{W/m}^2\ ^\circ\text{C}$

$h_c = 58.0\ \text{W/m}^2\ ^\circ\text{C}$

$h_{pa} = 17.0\ \text{W/m}^2\ ^\circ\text{C}$, during day

$\quad = 1\ \text{W/m}^2\ ^\circ\text{C}$, during night

$A_h = 8.5\ \text{m}^2$

$A_t = 10.3\ \text{m}^2$

$A_v = 4.5\ \text{m}^2$

$A_v' = 4.5\ \text{m}^2$

$M_w = 600\ \text{kg}$

$C_s = C_w = 4.2\ \text{kJ/kg}\ ^\circ\text{C}$

$\dot{m} = 0.0,\ 10\ \text{kg/hr}$

$\alpha' = 0.80$

$L_1 = 0.10\ \text{m}$

$L_2 = 0.50\ \text{m}$

$K_1 = 1.3\ \text{W/m}\ ^\circ\text{C}$

$K_2 = 0.721\ \text{W/m}\ ^\circ\text{C}$

$T_{wo} = T_{so} = 12\ ^\circ\text{C}$

The variation of the slurry temperature with the number of days for a conventional as well as a modified biogas plant have been shown in Fig. 2. From the calculations and the details given in Fig. 1, it can be seen that in the modified biogas plant a quasi-steady state condition is reached after 7-10 days of feeding the slurry into the digester (at the desired temperature for fermentation), while in the case of a conventional biogas plant it takes roughly 22-25 days. Hence in the biogas plant which is integrated with a solar water heater, gas production starts earlier than with a conventional plant because in the integrated plant the slurry is heated passively by solar energy.

It is also observed that water at a temperature of about 35-40°C can be obtained from solar water heater every morning at the time for hot-charging of the slurry while in other's case[6] it is

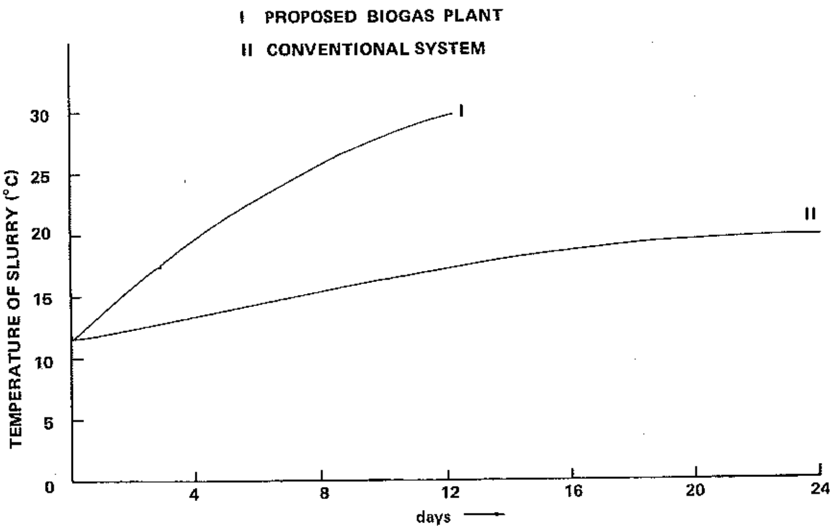

Fig. 2 Variation of slurry temperature with number of days for conventional as well as proposed biogas plant.

available only at noon time. It is due to the fact that night heat losses from cover is reduced by incorporating the insulation.

Here, it is important to note that the slurry temperature by this method under quasi-steady state condition is still higher by 2-3 °C than calculated by earlier workers by assuming a condition of quasi-steady state condition of the system. It is also observed experimentally that for a solar – assisted biogas plant anaerobic fermentation period is reduced by about 30-40% compared to the conventional biogas plant. Other conclusion under quasi-steady state conditions is same as concluded by Tiwari and Chandra.[6]

NOMENCLATURE

A	area (m^2)
A_v'	area of gas holder in contact with slurry (m^2)
C	specific heat (J/kg °C)
h_o	convective heat transfer coefficient from absorbing plate to the water (W/m^2 °C)
h_o'	overall heat transfer coefficient from absorbing plate to the ambient through glass cover (W/m^2 °C)
h_1	heat transfer coefficient from gas holder to gas (W/m^2 °C)
h_2	heat transfer coefficient from water to gas holder (W/m^2 °C)
h_3	heat transfer coefficient from gas to slurry (W/m^2 °C)
h_4	overall heat transfer coefficient from slurry to ground through basement of the digester (W/m^2 °C)
h_c	conductive heat transfer coefficient from gas holder to slurry (W/m^2 °C)
h_{pa}	heat transfer coefficient from gas holder to ambient (W/m^2 °C)
h_{rps}	radiative heat transfer coefficient from gas holder to slurry (W/m^2 °C)
K	thermal conductivity (W/m °C)
L	thickness (m)
M	mass (kg)
$\dot{m}$	mass flow rate (kg/hr)
T	temperature
t	time (hr)
α	absorptivity of absorber plate
α'	absorptivity of gas holder
τ	transmissivity of glass cover

Subscript

o	horizontal surface of gas holder
$1,2$	basement and ground[6]

∞	distant point in ground
b	absorbing plate
h	curved surface of gas holder
p	gas holder
s	slurry
t	total area ($A_t = A_h + A_v$)
v	vertical surface of gas holder
w	water

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