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Thermal modelling of photovoltaic thermal (PVT) integrated greenhouse system for biogas heating

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ABSTRACT

In this paper, the design and fabrication of photovoltaic thermal integrated greenhouse system (PVTIGS) for biogas heating has been done for climatic condition of IIT Delhi, India. PVTIGS can also be used for a number of applications like generating electricity, space heating, enhancing production of biogas, crop cultivation and crop drying, etc. Thermal modelling of proposed system (PVTIGS) without load has been developed based on energy balance equations. Further, with the help of thermal modelling the solar cell temperature, room temperature and solar cell efficiency have been calculated for a typical clear day of May. Experimental validation have been done on the basis of correlation coefficient (r) and root mean square percentage deviation (e) and found to be in fair agreement between theoretical and experimental values. Effect of packing factor, mass flow rate of air below module, absorptivity (degradation effect) and transmittivity (dusting effect) on thermal load levelling have been discussed. Electrical energy has been calculated and validated with experimental values. Further, thermal energy and overall thermal energy have been evaluated and found to be 11.18 kW h and 12.76 kW h respectively for a clear day without load.

1. Introduction

Globally, economies are investing phenomenally in further advancement of renewable energy technologies (RET's) through extensive research and development. In the recent years it has been realised that maximum energy generation capacity of RET's can be achieved by employing hybrid renewable energy systems (HRES's) as well as by having highly efficient storage technologies in place. The performance of HRES's doesn't rely on specific weather conditions. This is because HRES's comprise of more than one form of renewable energy technology (RET) which are integrated together and it works in tandem with smart grid. Hybrid systems are need of the hour because at any given point in time they can ensure uninterrupted power supply because at-least one RET is always functional. Another important step in this direction would be to bring about major improvements in the transmission grids that would eventually ensure efficient distribution of produced energy (Sodha et al., 1987; Chow, 2003, 2010; Tiwari and Sodha, 2006).

Biogas is an environmentally advantageous energy source which is mostly comprised of methane (60%) and carbon dioxide (35–40%). Moreover, biogas contains a low quantity of other gasses such as Ammonia (NH_3), hydrogen sulphide (H_2S), hydrogen (H_2), oxygen (O_2), nitrogen (N_2) and carbon monoxide (CO) (Herrero, 2011).

Tiwari et al. (1996), Sambo et al. (1995), Usmani et al. (1996), and Garba (1996) have suggested that the rate of biogas production and the retention period are functions of slurry temperature. The optimum temperature for anaerobic digestion is about 32–37 °C for getting maximum biogas yield. In northern India especially in Srinagar (Kashmir), India a drop in ambient temperature (T_a) of up to 2 °C is reported in winter season. This results in either drastic reduction or inhibition in the production of biogas. It was recommended by many researchers that in order to enhance the biogas production one has to increase the biogas slurry temperature inside the digester (Sodha et al., 1988; Subramanyam, 1989; Beba, 1988; Kitamura et al., 2007; Chae et al., 2008; Boe et al., 2009; Zielinska et al., 2013; Marsolek et al., 2014).

Kumar and Bai (2008) found that the yearly average slurry temperatures during study was 26.3 and 22.4 °C in experimentation and control biogas plants compared to the ambient of 17 °C. Further, the yearly average greenhouse chamber temperature measured was 29.1 °C in the biogas plant (experimental). It was also found that the gas yield and methane fraction recorded in control biogas plant was 11.5% and 6.5% lower than the experimental bio-

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Nomenclature

A_m	area of module (m^2)
A_i	area of all side wall of dryer (m^2)
Ac	cross sectional area of duct (m^2)
C	air conductance (W/m^2 K)
C_f	specific heat of air (J/kg K)
D	diameter of fan (m)
E_{el}	theoretical electrical energy (kW h)
$E_{el,ex}$	experimental electrical energy (kW h)
hi	heat transfer coefficient (htc) inside solar drying chamber (W/m^2 K)
h_o	heat transfer coefficient from top of module to ambient (W/m^2 K)
h_1	heat transfer coefficient from wall of dryer to ambient (W/m^2 K)
$I(t)$	solar intensity (W/m^2)
$I(i)$	solar intensity on the wall of drying chamber (W/m^2)
k_g	thermal conductivity of glass and module (W/m K)
Lg	thickness of glass cover and glazing (m)
$\dot{M}_f$	mass flow rate of air (kg/s)
N	fan speed (RPM)
T_a	ambient temperature (°C)
T_c	cell temperature (°C)
T_r	drying chamber temperature (°C)
U_{bo}	heat transfer coefficient from bottom of the glazing to drying chamber (W/m^2 K)
U_{bo1}	heat transfer coefficient from bottom of the glazing to drying chamber (W/m^2 K)
U_{tca}	heat transfer coefficient from top of module to ambient air (W/m^2 K)
α_c	absorptivity of solar cell
β_c	packing factor of module
η_c	solar cell efficiency
η_m	module efficiency
V	wind velocity (m/s)
v_1	wind velocity through duct (m/s)
v_2	average wind velocity around the wall (m/s)
τ_g	transmittivity of glass

gas plant respectively. Abdeshahian et al. (2016) concluded that the biogas potential of 4589.49 million m^3 per year could be generated from animal waste in Malaysia in 2012 which may provide an electricity production of 8.27×10^9 kW h/year. Further, it was also added in conclusion that anaerobic digestion of animal waste decreases their harmful impacts on the environment which leads to enhancing public health. To making the biogas gas system more productive photovoltaic integrated biogas systems came into existence in which roof area could be utilize for power production which is beneficial for rural areas where grid connectivity is not available. Many researchers have been done extensive work on PV integrated systems.

Photovoltaic module is a packaged interconnected assembly of photovoltaic cells. PV module generates electricity by harnessing sun's incident radiation. Kern and Russell (1978) were the first to develop and design photovoltaic thermal (PVT) systems. Hendrie (1979) analysed a theoretical model of PVT system and reported that they give improved energy yield per unit area of the panel as compared to a simple PV system. Incident radiation result in a substantial increase in the temperature of the PV module causing any or both of these undesirable consequences that is (i) a drop in cell efficiency (typically 0.4% per °C rise for C-Si cells) (ii) a permanent structural damage to the module due to prolonged thermal stress (Barnwal and Tiwari, 2008). Thus, a better design of the PV module would be wherein the heat energy gained by the PV module is transferred to the fluid flowing next to the module and subsequently this heated fluid gets re-used. This phenomenon would significantly reduce the solar cell's temperature (T_c) thereby resulting in an evident increase in the electrical and overall efficiency of the system. Such systems are known as photovoltaic thermal (PVT) systems. Another significant drawback of majority of the conventional PV systems is their high initial cost and limited electrical output in comparison to the input solar energy available to them. Thus, we need to work on making PV modules highly competitive. Different PV modules have already demonstrated substantial improvements and transformations over the past 40 years and are further expected to undergo developments in the coming decades. Also, the evolvement of PVT hybrid solar technologies is a major step in this direction (Norton et al., 2011; Chow et al., 2009; Nayak and Tiwari, 2010; Vats and Tiwari, 2012a,b).

Nayak and Tiwari (2009) evaluated the annual thermal and exergy performance of a photovoltaic thermal (PVT) and earth air heat exchanger (EAHE) system, which was integrated with a greenhouse and the experimental set up was located at IIT Delhi, India. The study was carried out for five different climatic conditions namely for: Srinagar, Mumbai, Jodhpur, New Delhi and Bangalore. It was observed that maximum annual overall thermal energy, annual electrical energy savings and annual exergy were obtained for Jodhpur's climatic condition due to higher solar intensity and sunshine hours and the lowest was observed for Srinagar. Dubey and Tiwari (2009) have analysed photovoltaic thermal flat plate collectors connected in series. Prabhakant and Tiwari (2008, 2009) developed the thermal model of photovoltaic thermal flat plate collector integrated with biogas plant, known as active photovoltaic thermal biogas plant under Indian climatic conditions.

Dubey et al. (2009) had shown in his work that PVT system with duct give higher electrical efficiency as compared to the systems without duct. Delisle and Kummer (2014) have simulated the performances and proved that BIPVT systems are more efficient than solar thermal collectors and PV modules working independently for the same purpose. Singh (2013) has worked on a PVT mixed mode dryer and a greenhouse dryer integrated with PV modules at two different locations. Both the systems were used for drying of crops and DC fan were also installed in the system in order to regulate the circulation and ensure faster removal of humid air. Vats and Tiwari (2012a,b) have calculated electrical and thermal energy outputs for a building integrated semitransparent photovoltaic thermal (BISPVT) system integrated to the roof of a room. Agrawal and Tiwari (2011) have studied energy and exergy analysis of a hybrid micro-channel photovoltaic thermal (MCPVT) module based on a proposed micro-channel solar cell thermal (MCSCT) under constant mass flow rate of air in terms of design and climatic parameters. The performance in terms of overall annual thermal and exergy gain and exergy efficiency of micro-channel photovoltaic thermal module have been evaluated by considering four weather conditions for different climatic conditions of India. Further, analysis has also been carried out for single channel photovoltaic thermal (SCPVT) module and the results of micro-channel photovoltaic thermal module and single channel photovoltaic thermal module have been compared. They have reported an overall annual thermal and exergy gain for MCPVT module for Srinagar climatic conditions.

Rozario and Pearce (2015) carried out a study by simulation of the optimal dispatch strategy for a-Si: H based PVT by study