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Energy and exergy analysis of photovoltaic/thermal integrated with a solar greenhouse

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ABSTRACT

In this paper, an attempt has been made to validate the thermal model with experimental results of a typical day August, 25, 2006 for clear weather condition of New Delhi. An energy and exergy analysis for the prediction of performance of a photovoltaic/thermal (PV/T) collector integrated with a greenhouse at I.I.T, Delhi, India has been carried out. The analysis is based on quasi-steady state condition. Experiments have been conducted extensively during period from June 2006 to May 2007, for annual performance. Numerical computation has been carried out for a typical day only for validation. It is observed that the theoretical value of solar cell, tedlar back surface and greenhouse room air temperatures is approximately equivalent to the experimental values. The predicted and measured values of solar cell, tedlar back surface and greenhouse air temperatures have been verified in terms of root mean square of percent deviation (7.05–17.58%) as well as correlation coefficient (0.95–0.97) and both exhibit fair agreement. Exergy analysis calculations of the PV/T integrated greenhouse system show an exergy efficiency level of approximately 4%.

1. Introduction

Heating of greenhouse is one of the most important and essential requirements for proper growth of summer growing crops in winter, Tiwari [1]. Greenhouse heating can be carried out either by passive or an active method. The study of greenhouse heating by the passive method has also been made by many scientists, Tiwari and Dhiman [2], Abak et al. [3] and Santamouris et al. [4]. The passive heating may be realized through water storage, rock bed storage, presence of north wall, mulching, phase changing material, movable insulation and thermal curtain etc. Among passive heating modes a thermal curtain or thermal screen is one of the most practical and appropriate means for reducing the energy consumption in greenhouse, Bailey [5] and Barrel et al. [6]. Active heating methods are ground collector, the ground geothermal water and an earth–air heat exchanger. Thermal heating of greenhouse using the active method has been investigated by many researchers namely Connellan [7], Santamouris et al. [8], Bargach et al. [9] and Jain and Tiwari [10].

Jones and Underwood have studied the temperature profile of a photovoltaic (PV/T) module in non-steady conditions. They have carried out experimental observations for cloudy as well as clear sky conditions. They found that PV module temperature varies in the range of 27–52 °C for an ambient air temperature (24.5 °C). The carrier of thermal energy associated with the PV module can be air or water. The integrated arrangements for utilizing thermal energy as well as electrical energy, with a photovoltaic module are referred to as the hybrid PV/T system [11]. The rate of the thermal energy obtained from hybrid (PV/T) system is supplied to the greenhouse for heating purpose. Tiwari and Sodha [12] have studied the thermal performance of a hybrid photovoltaic thermal (PV/T) air collector for New Delhi climatic condition.

Chow [13] analyzed the performance of photovoltaic-thermal collector by explicit dynamic model and a thermal efficiency of 60% has been observed. If the hot air available from PV/T air collector is used to heat greenhouse then it is referred as hybrid greenhouse. Sujata and Tiwari [14] have studied the performance evaluation of a hybrid PV/T integrated greenhouse system. Design, construction and testing of hybrid photovoltaic integrated greenhouse dryer have been studied by Barnwal and Tiwari [15]. Dincer et al. [16] have studied energetic performance of two geothermal district heating systems for building applications and found energy efficiencies for Balcova geothermal district heating system and Salihli geothermal district heating system to be 39.36% and 59.31%, respectively.

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Nomenclature

A	area (m^2)
B	breadth (m)
c_a	specific heat of air ($J\,kg^{-1}\,°C^{-1}$)
c_p	specific heat of plant ($J\,kg^{-1}\,°C^{-1}$)
dx	elemental length (m)
$\dot{E}x_{in}$	exergy input to the greenhouse (kWh)
$\dot{E}x_{out}$	exergy output to the greenhouse (kWh)
$\dot{E}x_{th}$	exergy thermal energy to the greenhouse (kWh)
$(\dot{E}x_{th})_{monthly}$	monthly exergy thermal energy to the greenhouse (kWh)
$(\dot{E}x_{th})_{yearly}$	yearly exergy thermal energy to the greenhouse (kWh)
$\dot{E}x_{work}$	exergy of work rate (kWh)
h_{p1}	penalty factor due to presence of solar cell material, tedlar and EVA
h_T	conductive heat transfer coefficient through tedlar ($W\,m^{-2}\,°C^{-1}$)
h_t	convective heat transfer coefficient from back surface of tedlar to the working fluid ($W\,m^{-2}\,°C^{-1}$)
$h_{g\infty}$	heat transfer coefficient from floor to larger depth of ground ($W\,m^{-2}\,°C^{-1}$)
h_{gr}	heat transfer coefficient from greenhouse floor to room ($W\,m^{-2}\,°C^{-1}$)
h_{grr}	heat transfer coefficient from greenhouse to greenhouse air ($W\,m^{-2}\,°C^{-1}$)
$I(t)$	incident solar intensity on inclined PV module surface ($W\,m^{-2}$)
k	thermal conductivity ($W\,m^{-1}\,°C^{-1}$)
m_a	mass of air (kg)
m_p	mass of plant (kg)
N_o	number of air changes per hour (rpm)
$(\dot{Q}_u)_{daily}$	daily rate of useful thermal energy (kWh)
t	time (s)
T_a	ambiant temperature (°C)
T_c	solar cell temperature (°C)
T_{bs}	tedlar back surface temperature (°C)
T_r	greenhouse room air temperature (°C)
T_∞	temperature at larger depth, Infinity (°C)
u	duct air velocity ($m\,s^{-1}$)
U_T	conductive heat transfer coefficient from solar cell to ambient through top and back surface ($W\,m^{-2}\,°C^{-1}$)
U_{tT}	overall heat transfer coefficient from glass to tedlar through solar cell ($W\,m^{-2}\,°C^{-1}$)
V	volume of greenhouse (m^3)

Greek symbols

α_c	absorptivity of solar cell, dimensionless
α_T	absorptivity of tedlar, dimensionless
α_p	absorptivity of plant, dimensionless
α_g	absorptivity of floor, dimensionless
$(\alpha\tau)_{eff}$	effective transmittance-absorptance product for greenhouse
β_c	packing factor of solar cell, dimensionless
η_c	efficiency of solar cell, dimensionless
η_{EX}	exergy efficiency of greenhouse (%)
v	wind velocity ($m\,s^{-1}$)
ρ	density of air ($kg\,m^{-3}$)
ζ_G	transmissivity of glass, dimensionless

In this paper, an attempt has been made to validate the developed thermal model with experimental values for a typical day for clear day conditions. The monthly energy and exergy analysis for PV/T integrated greenhouse has also been carried out.

2. Experimental set-up and observations

There are two PV arrays, each consists of 8 PV modules of rating 75 W; short circuit current (I_{sc}) = 4.8 A; rated current 4.4 A; open circuit voltage (V_{oc}) = 21.7 V; rated voltage 17.0 V (Siemens solar industries, camarillo) with an effective area of 0.605 m^2. The PV modules, each are connected in series and mounted on a wooden structure. The PV module with a wooden structure is placed on a steel frame. The inclination of the frame is maintained at around 45° for receiving the maximum solar radiation. Infrared thermometer has also been provided to measure the temperature of the exposed surface (solar cell) and unexposed surface (tedlar back surface) of the module. One fan of capacity 12 W has been provided at the outlet to induce the flow of air inside the greenhouse. The power generated by solar modules is stored in a set of 12 D.C. batteries of rating each 6 V and 180 Ah-10 h. There is an inverter of rating 2.1 KVA is employed for running AC equipments.

The experimental set-up shown in Fig. 1 is Photovoltaic Integrated Solar Greenhouse System.

2.1. Working principle of PV integrated greenhouse

Front view of PV/T integrated greenhouse has been shown in Fig. 2. These PV panels are integrated with greenhouse for generating the required electrical power to run the accessories. During daytime the solar radiation falls on the greenhouse, which increases temperature of the inside greenhouse. In a clear day the temperature may go up to 50–55 °C. The rise in temperature depends upon the weather condition. In winter season, the lowest outside temperature may lie between 2 and 10 °C. Due to low temperature the growth of plants reduces. The greenhouse helps in increasing the temperature in winter between 40 and 45 °C. For maintaining the air movement uniform inside the greenhouse, a DC fan is operated continuously.

When the solar radiation falls on the roofs and walls of the greenhouse, it enters inside the greenhouse through the transparent canopy cover. Part of the solar radiation is lost due to the transparent north wall cover. The solar radiation is absorbed by the ground and re-emitted in the form of long wavelength radiation,

Fig. 1. Picture of experimental set-up at solar energy park, IIT Delhi campus.