Energy and Buildings 41 (2009) 863–870

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy and exergy analysis of PV/T air collectors connected in series

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ARTICLE INFO

Article history:
Received 4 November 2008
Received in revised form 25 February 2009
Accepted 2 March 2009

Keywords:
Photovoltaic
Exergy
Thermal energy
Efficiency
Solar collectors

ABSTRACT

In this paper an attempt has been made to derive the analytical expressions for N hybrid photovoltaic/thermal (PV/T) air collectors connected in series. The performance of collectors is evaluated by considering the two different cases, namely, Case I (air collector is fully covered by PV module (glass to glass) and air flows above the absorber plate) and Case II (air collector is fully covered by PV module (glass to glass) and air flows below the absorber plate). This paper shows the detailed analysis of energy, exergy and electrical energy by varying the number of collectors and air velocity considering four weather conditions (a, b, c and d type) and five different cities (New Delhi, Bangalore, Mumbai, Srinagar, and Jodhpur) of India. It is found that the collectors fully covered by PV module and air flows below the absorber plate gives better results in terms of thermal energy, electrical energy and exergy gain. Physical implementation of BIPV system has also been evaluated. If this type of system is installed on roof of building or integrated with building envelope will simultaneously fulfill the electricity generation for lighting purpose and hot air can be used for space heating or drying.

1. Introduction

The thermal energy plays an important role in human's life. It can be generally utilized in the form of either high grade (high temperature) or low grade (low temperature). Jones and Underwood [1] have studied the temperature profile of photovoltaic (PV) module in an un-steady state condition. They performed experiments for clear as well cloudy day condition and observed that the PV module temperature varies between 300 K and 325 K (27–52 °C) for an ambient air temperature of 297.5 K (~24.5 °C). The thermal energy associated with PV module may either be removed (carried away) by air or water. System is referred as hybrid PV/T system.

Hybrid PV/T system has following applications:

1 Air heating (Bhargava et al. [2], Tiwari et al. [3], Odeh et al. [4], Vorobiev et al. [5], Cartmell et al. [6], Hegazy [7], Infield et al. [8], Tripanagnostopoulos et al. [9], Prakash [10]).
2 Water heating (Tripanagnostopoulos et al. [9], Tiwari and Sodha [11], Sandnes and Rekstad [12], Zakharchenko et al. [13], Chow [14], Garg et al. [15], Kalogirou [16], Zondag et al. [17]).

Tiwari et al. [3] have analyzed performance of solar air collector for composite climate of India and concluded that an overall efficiency of hybrid PV/T thermal system increases by 18% due to gain of thermal energy in addition to electrical energy. The application of ventilated photovoltaic (VPV) systems incorporating hybrid PV/T collectors is a viable method of cost saving due to the combined provision of electrical power and heated air for use within the building. Since in this technology, air is actively passed behind the PV modules, which helps in keeping cells temperature low to maintain higher cell efficiency. The applications of roof mounted, multi-operational ventilated photovoltaic and solar air collector were studied by Cartmell et al. [6]. Prakash [10] has developed a mathematical model for transient analysis of solar collector for co-generation of electricity and hot air/water by considering the various flow rates and duct depths for summer conditions of Delhi. He has concluded that the cell efficiency was marginally improved, while in addition, an average thermal efficiency of about 50–70% for water heating and 17–51% for air heating was obtained.

The unglazed hybrid photovoltaic/thermal with booster diffuse reflector integrated with horizontal roof of a building is analyzed by Tripanagnostopoulos et al. [9] and suggested that PV/T system with reflector gives clearly higher electrical and thermal output. Infield et al. [8] have derived an overall heat loss coefficient (U) and thermal energy gain factor (g) for ventilated vertical PV module and double glazed window (PV facades). Steady state analysis have been used to determine ventilation gains and transmission losses in terms of irradiation (solar radiation) and various heat transfer process involved in facades and observed that the electrical efficiency of PV module is improved due to low operating temperature by using ventilated facades (generally below 45 °C). Hegazy [7] and Sopian et al. [18] have investigated the glazed photovoltaic/thermal air (PV/T

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doi:10.1016/j.enbuild.2009.03.010

Nomenclature

A	area (m^2)
b	width of collector (m)
C	air cavity (W/m^2)
C_f	specific heat (J/kg K)
F_R	flow rate factor
h	heat transfer coefficient (W/m^2)
$I(t)$	incident solar intensity (W/m^2)
K_B	thermal conductivity of brick wall (W/m)
K_T	thermal conductivity of tin (W/m)
K_W	thermal conductivity of wooden structure (W/m)
L	length of collector (m)
L_B	thickness of brick wall (m)
L_T	thickness of tin (m)
L_W	thickness of wooden structure (m)
$\dot{m}$	rate of flow of water mass (kg/s)
M_a	mass of air inside room (kg)
PF_1	penalty factor first
PF_2	penalty factor second
$\dot{Q}_u$	rate of useful energy transfer (kW)
T	temperature (°C)
U_{L1}	An overall heat transfer coefficient from blacken surface to ambient (W/m^2 K)
$U_{t\ c,a}$	an overall heat transfer coefficient from solar cell to ambient through glass cover (W/m^2 K)
V	air velocity (m/s)
w	thickness of collector (m)

Subscripts

a	ambient
c	solar cell
eff	effective
f	fluid (air)
g	glass
m	module
p	plate
r	room

Greek letters

α	absorptivity
$(\alpha\tau)_{eff}$	product of effective absorptivity and transmitivity
β	packing factor
η_i	an instantaneous thermal efficiency
τ	transmitivity

air) system for single and double pass air heater for space heating and drying purposes. They have also developed a thermal model for each system and observed that thermal energy for glazed PV/T system was increased with lower electrical efficiency due to high operating temperature.

Recently, Zondag [19] has carried out rigorous review on PV–thermal collector systems, carried out by various scientists till 2006. His review included the history and importance of photovoltaic hybrid system and its application in various sectors. It also includes characteristics equations, study of design parameters, and marketing, etc. The relations between energy and exergy, energy and sustainable development, energy policy making, exergy and the environment and exergy in detail are reported by Dincer [20].

In this paper an attempt has been made to derive the analytical expressions for N hybrid photovoltaic/thermal (PV/T) air collectors connected in series. The performance of collectors are evaluated by considering the two different cases, namely,

Case I: Air collector is fully covered by PV module (glass to glass) and air flows above the absorber plate.
Case II: Air collector is fully covered by PV module (glass to glass) and air flows below the absorber plate.

The monthly gain in energy, exergy and electrical energy of the air collector fully covered by PV module is evaluated by considering four types of weather conditions for five different cities (New Delhi, Bangalore, Mumbai, Srinagar, and Jodhpur) of India. These cities are classified under the five different climatic condition of India.

The four type of weather conditions are defined as,

Type a: The ratio of daily diffuse to daily global radiation is less than or equal to 0.25 and sunshine hours greater then or equal to 9 h.
Type b: The ratio of daily diffuse to daily global radiation between 0.25 and 0.50 and sunshine hours between 7 h and 9 h.
Type c: The ratio of daily diffuse to daily global radiation between 0.50 and 0.75 and sunshine hours between 5 h and 7 h.
Type d: The ratio of daily diffuse to daily global radiation is greater than or equal to 0.75 and sunshine hours less then or equal to 5 h.

The monthly average data of solar radiations for different climatic conditions was obtained from Indian Metrological Department (IMD), Pune. The glass to glass PV module was manufactured by Central Electronics Ltd. (CEL), Sahibabad, Ghaziabad (U.P.).

2. Thermal modeling

The cut sectional view of air collector of Case I (air collector is fully covered by PV module (glass to glass) and air flows above the absorber plate) and Case II (air collector is fully covered by PV module (glass to glass) and air flows below the absorber plate) are shown in Fig. 1.

Following assumptions have been made in order to write the energy balance equation for each component of photovoltaic/thermal (PV/T) glass to glass air collector.

- One dimensional heat conduction is good approximation for the present study.
- The system is in quasi-steady state.
- Temperature of solar cell and back surface of PV module are same.
- The glass cover of PV module is at uniform temperature.
- The ohmic losses in the solar cell are negligible.

The energy balance equations for each component of air collector by considering elemental region of '*bdx*' in the flow direction can be written as

2.1. Case I: air collector is fully covered by PV module (glass to glass) and air flows above the absorber plate (Fig. 1a)

2.1.1. For solar cells of PV module

$$\alpha_c\tau_g\beta_c I(t)bdx = [U_{tc,a}(T_c - T_a) + h_{c,f}(T_c - T_f)]bdx + \tau_g\eta_c\beta_c I(t)\cdot bdx$$

[The rate of solar energy available on solar cell] = [An overall heat loss from top surface of cell to ambient] + [The rate of heat transfer from cell to flowing fluid] + [The rate of electrical energy produced] (1a)