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Performance evaluation of *N*-photovoltaic thermal (PVT) water collectors partially covered by photovoltaic module connected in series: An experimental study

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ABSTRACT

In present communication, an experimental study has been carried out to evaluate the performance of series connected photovoltaic thermal (PVT) water collector in terms of overall thermal energy gain and overall exergy gain. Earlier developed theoretical model has been validated by performing the experiment in a clear sky day, hazy day and partially cloudy day for New Delhi climatic condition. It was found that theoretical results were in good agreement with experimental results. The annual energy gain, exergy gains, CO_2 mitigation, energy matrices and carbon credit of the system have also been discussed. The energy pay-back time was found to be 1.50 and 14.19 years on overall thermal energy and exergy basis respectively. Carbon credits earned in a year were Rs. 6321.70 for overall thermal energy gain and Rs. 667.30 for overall exergy gain. For 30 years of life time, cost of one unit of electricity was estimated to be Rs. 1.53 on overall thermal energy basis however it was Rs. 14.45 on overall exergy basis.

1. Introduction

The rapid worldwide industrialization is increasing the amount of greenhouse gases heavily in our environment. The depletion of fossil fuels with continuous growing world population enhances the demand of energy in every sector significantly. Renewable energy is an important means of reducing greenhouse gases emission. Simultaneously it can meet the energy security challenges.

Solar water collector is a renewable energy technology that harnesses the solar energy and produces hot water utilizing thermal energy from sun. Hot water is used for bathing, washing utensils, cooking and for other domestic purposes which is usually produced by burning firewood or by fossil fuel energy such as kerosene oil, liquid petroleum gas (LPG), coal and electricity. Therefore production of hot water using solar energy can reduce the consumption of fossil fuels. Further the photovoltaic thermal (PVT) combines photovoltaic technology and solar thermal collector together to produce heat and electricity simultaneously. PVT collector can produce more electrical and thermal energy than individual PV module and solar thermal collector (Chow, 2003). These systems are appropriate for the places where available surface area is limited. Also the life of these systems is around 20–30 years (Kern and Russel, 1978; Bergene and Lovvik, 1995; Chow, 2003; Hepbasli, 2008; Dupeyrat et al., 2014). Due to such attractive features PVT technology is expected to grow rapidly in future.

The first PVT collector was proposed by Kern and Russel (1978). After that various researches on PVT water collector have been carried out by many researchers both experimentally and numerically. He et al. (2006) stated that the PVT water collector in natural mode of operation gives better energy saving efficiency per unit area as compared to the conventional thermosyphon water collector system. Chow et al. (2009) investigated different PVT water collector and found that the glazed PVT water collector are most preferable for thermal energy applications whereas for electrical energy applications unglazed PVT water systems are found to be better. Chow (2010) reviewed the photovoltaic thermal technologies covering many important aspects as experimental, computational, testing and design procedure, analytical tools and geographical locations. It was concluded in his studies that choice of PVT system depends on various parameters such as geographical locations, availability of solar radiation, utility, application and cost

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Nomenclature

α_c	absorptivity of the solar cell
$A_c = WL_c$	area of the glazing (m^2)
$A_m = WL_m$	area of the module (m^2)
β_0	temperature coefficient ($^\circ C^{-1}$)
β	packing factor of PV module
$C_f = C_w$	specific heat of water (J/kg K)
CRF	capital recovery factor
e	root mean square percent deviation
F'	collector efficiency factor
FF	fill factor
h_i	heat transfer coefficient for space between the glazing and absorbing plate (W/m^2 K)
h_i'	heat transfer coefficient from bottom of PVT water collector to the ambient (W/m^2 K)
h_o	heat transfer coefficient from top of PVT water collector to the ambient (W/m^2 K)
h_{pf}	heat transfer coefficient from blackened plate to the water (W/m^2 K)
i	interest rate
$I(t)$	solar intensity (W/m^2)
K_g	thermal conductivity of glass (W/m K)
K_i	thermal conductivity of insulation (W/m K)
K_p	thermal conductivity of absorption plate (W/m K)
L_c	length of PVT water collector covered by glazing (m)
L_g	thickness of glass (m)
L_i	thickness of insulation (m)
L_m	length of PVT water collector covered by PV module (m)
L_p	thickness of absorption plate (m)
$\dot{m}_f$	mass flow rate of water (kg/s)
M_w	mass of water in tank (kg)
η_c	solar cell efficiency
η_m	module efficiency
NPV	net present value
PF_1	penalty factor due to the glass cover of PV module
PF_2	penalty factor due to the absorption plate for the portion covered by PV module
PF_3	penalty factor due to the absorption plate for the portion covered by glazing
r	correlation coefficient
R_{ex}	unit cost on exergy basis
R_{th}	unit cost on overall thermal energy basis
ρ	density of water
τ_g	transmissivity of the glass
T_a	ambient temperature (°C)
T_c	solar cell temperature (°C)
T_{fi}	inlet water temperature (°C)
T_{foc}	water temperature up to the portion covered by glazing (°C)
T_{fom}	water temperature up to the portion covered by PV module (°C)
T_{foN}	outlet water temperature at the end of the N^{th} PVT water collector (°C)
T_p	temperature of absorption plate (°C)
T_w	temperature of water in tank (°C)
$(UA)_{tk}$	overall heat transfer coefficient from water tank to ambient (W/m^2 K)
$U_{L,c}$	overall heat transfer coefficient from glazing to ambient (W/m^2 K)
$U_{L,m}$	overall heat transfer coefficient for module, from module to the ambient (W/m^2 K)
$U_{tc,a}$	overall heat transfer coefficient from solar cell to the ambient through top surface (W/m^2 K)
$U_{tc,p}$	overall heat transfer coefficient from back surface of solar cell to the absorption plate (W/m^2 K)
$U_{tp,a}$	overall heat transfer coefficient from absorption plate to the ambient (W/m^2 K)
Unacost	uniform annualized cost
W	width of PVT water collector (m)

effectiveness of the system. The exergy analysis of different solar energy applications (Saidur et al., 2012) concludes that thermal efficiency is insufficient for choosing a system with solar energy application rather exergy efficiency plays a vital role in choosing any system utilizing solar energy. Zhang et al. (2012) presented recent status of research, development and practical applications of PVT systems and suggested that still more emphasis is required for economic and energy efficient systems, optimization of configuration, integrated applications and environmental issues. Antonanzas et al. (2015) studied the effect of different gases filled between PV module and absorber plate on the convective heat transfer coefficient of the fully covered single PVT flat plat water collector. The convective heat transfer in space between PV module and absorber plate has been evaluated for the different gases. The environmental and economic concerns have also been discussed in their study and inferred that Argon was best suited for the experimental validation. Motte et al. (2013) and Yin et al. (2013) studied the PVT water collector assembly integrated with building through a phase change material (PCM) for thermal energy storage. It was found that PCM allows storage of solar thermal energy for longer time and it also renders use of stored thermal energy for advanced technological application where water or air has inability as thermal energy carriers. Tian and Zhao (2013) reviewed the solar thermal collectors (water collector, air collector, concentrating and non-concentrating collectors, PVT collectors) and energy storage in solar thermal applications and observed that the PVT collector is better among all the studied collectors. Zhang et al. (2014) studied the annual energy performance, CO_2 emission, economic analysis and environmental benefits for cold (London), warm (Shanghai) and hot (Hong Kong) areas. It was found that the commissioning of any PVT system at any place depend upon three crucial factors namely energy efficiency, economic revenue and environmental benefits. Aste et al. (2015) analyzed the glazed PVT water collectors using thin film PV technology (top amorphous and bottom microcrystalline layer) and roll – bond flat plate collector. The analysis was done for a fully covered single collector and it was concluded that the PVT technology give better overall efficiency compared to PV module. Rejeb et al. (2015) developed and experimentally validated a mathematical model and done a parametric study for the fully covered tube in sheet single PVT collector. Tiwari and Sodha (2006) developed the theoretical model for water heating system integrated with fully covered single PV module (unlike the present case i.e. partially covered series connected photovoltaic thermal flat plate collector (PVT-FPC)) and validated the model using experimental results of earlier research. In the present study, the analysis has been carried out for water heating system integrated with series connected partially covered PVT flat plate collector which can be optimized (area of the PV modules, area of the glazing, packing factor, number of collectors and mass flow rate) as per the desired outlet water temperature and electricity production for the given storage capacity. Chow et al. (2006) constructed and evaluated the performance of the box type single (unlike the present case i.e. N-series connected PVT-FPC) flat plate collector partially covered by PV module. Their analysis has been