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Analysis of series connected photovoltaic thermal air collectors partially covered by semitransparent photovoltaic module

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ABSTRACT

In the present work, an analysis for series connected photovoltaic thermal (PVT) air collectors has been done. The analytical expressions for efficiencies (electrical and thermal), air temperature, thermal energy and exergy, and electrical energy have been derived for two cases (Case A: inlet portion covered by semi-transparent PV module and Case B: outlet portion covered by semitransparent PV module). The energy matrices, uniform annualized cost and carbon credits have also been estimated. It was found that, for lower mass flow rate and less number of series connected collectors, Case A gives better performance whereas at higher mass flow rate and large number of series connected collectors, both cases give similar results. The energy pay-back time for overall thermal energy saving was 1.12 years; and for exergy saving it was 7.72 years. For 30 years life time and 4% interest rate, the uniform annualized costs were 0.016 $/kW h (for overall thermal energy saving) and 0.109 $/kW h (for exergy saving).

1. Introduction

The Photovoltaic thermal (PVT) collectors are the system which produces thermal as well as electrical energy from a single unit which reduces the area requirement for its installation. The PVT solar collectors with water/air as a working fluid were first introduced in 1978 (Kern and Russell, 1978; Florschuetz, 1979). Cox and Raghuraman (1985) studied the effect of area covered by solar cell (pasted on the absorber plate) on the performance of PVT air collectors. They predicted that above 65% area covered by the solar cells, the thermal performance of the system was degraded. Bhargava et al. (1991) computed the optimum area required for solar cell to run the fan for a particular application of PVT air collector. Garg et al. (1991) found that the optimum solar cell area for solar drying applications can be reduced by using booster reflectors.

Different flow patterns for air flow (Sopian et al., 1996, 2000; Hegazy, 2000) and effect of fins (Tonui and Tripanagnostopoulos, 2007; Kumar and Rosen, 2011) was analyzed. It was found that double – pass flow patterns and PVT air collectors with fins gave better performance than the single pass flow pattern. Different designs of fully covered PVT air collectors, covered by PV modules (Tiwari and Sodha, 2006, 2007; Tiwari et al., 2006) have been analyzed. It was concluded that glazed system perform better than the unglazed system. Dubey et al. (2009a) studied the series connected PVT air collectors (fully covered by semitransparent PV modules) in two different configurations. They predicted that, for higher number of fully covered PVT air collectors, air flow below the absorber plate gives better performance. Shahsavar and Ameri (2010) analyzed the PVT air collectors for natural and forced flow with different number of fans. They concluded that optimization of number of fans was necessary for maximum electrical output from a given configuration.

The building-integrated photovoltaic thermal (BIPVT) systems were studied (i) utilizing unglazed transpired collector (Athienitis et al., 2011), (ii) utilizing air as a thermal energy carrier (Norton et al., 2011; Sohel et al., 2014; Gaur and Tiwari, 2015) and (iii) with different PV technology (Vats and Tiwari, 2012). It was concluded from the above studies that unglazed transpired collector improves the electrical performance of the building, amorphous silicon PV modules are better for space heating and systems without air duct are more suitable for the space heating applications.

Different array configurations of PVT air collector fully covered by PV modules (semitransparent and opaque) were theoretically (Rajoria et al., 2012, 2013; Agrawal and Tiwari 2011c, 2013b) and experimentally (Agrawal and Tiwari, 2011a,b) studied in indoor (Solanki et al., 2009) as well as outdoor (Agrawal and Tiwari, 2012, 2013a, 2015) test conditions for Indian climatic conditions.

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Nomenclature

α_c	solar cell absorptivity
A_c	glazing area (m^2)
A_m	module area (m^2)
A_s	cross-sectional area of air duct (m^2)
β_0	temperature coefficient (°C^{-1})
β	packing factor
C_f	specific heat of air (J/kg K)
CRF	capital recovery factor
cCO_2	cost of one tone of CO_2
xCO_2	amount of CO_2 (in tones) mitigated in a year
D	air duct depth
$E_{annual,sol}$	total annual solar energy input on the PVT air collector
E_{in}	total embodied energy of the PVT air collector
E_{out}	annual energy/exergy saving from PVT air collector
h_i	heat transfer coefficient for space between the glazing and absorbing plate (W/m^2 K)
h_i'	heat transfer coefficient (h.t.c.) between bottom of PVT air collector and ambient through insulation (W/m^2 K)
h_o	h.t.c. between top of PVT air collector and ambient through glass cover (W/m^2 K)
h_{pf}	h.t.c. between blackened plate and air (W/m^2 K)
i	interest rate
$I(t)$	global solar radiation (W/m^2)
k	thermal conductivity of air (W/m K)
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	length of air collector
L_c	length of glazing (m)
L_g	glass thickness (m)
L_i	insulation thickness (m)
L_m	length of PV module (m)
L_p	thickness of absorption plate (m)
$\dot{m}_f$	mass flow rate of air (kg/s)
ν	kinematic viscosity of air (s/m^2)
Nu	Nusselt number
η_c	solar cell efficiency
η_m	module efficiency
NPV	net present value
P	present/capital cost of PVT air collector
Pr	Prandtl number
Re	Reynolds number
R_{ex}	unit cost (for exergy saving)
R_{th}	unit cost (for overall thermal energy saving)
$R_1, R_1, \ldots, R_n$	operational, maintenance and pump replacement costs of PVT air collector
$R_{3,1}, R_{6,2}, \ldots, R_{n,n}$	painting, cleaning and glass replacement costs of PVT air collector
ρ	density of air
T	life time of PVT air collector
τ_g	transmissivity of the glass
T_a	ambient temperature (°C)
T_c	solar cell temperature (°C)
T_{fi}	inlet air temperature (°C)
T_{foN}	outlet air temperature at the end of the N^{th} PVT air collector (°C)
T_p	temperature of absorber plate (°C)
$Unacost$	uniform annualized cost
W	width of PVT air collector (m)
v	velocity of air inside duct (m/s)

Ji et al. (2014) experimentally studied a tri-functional PVT collector which can efficiently operate for longer time period in a year compared to other solar collectors. Arcuri et al. (2014) optimized the duct depth, number of ducts and mass flow rate of the PVT air collectors for cooling of PV module. Incorporation of PVT air collectors in BIPVT system was suggested for better performance. Guo et al. (2015) experimentally validated the steady state and dynamic model for the tri-functional PVT collector. The system was investigated with different wind speed, mass flow rates and inlet temperatures. The system gives the better annual performance compared to conventional solar thermal collectors.

Elsafi and Gandhidasan (2015) compared (parametric comparison; effect of fins; and fin material) the compound parabolic concentrated PVT (CPC-PVT) collector with the double pass flat plate PVT collectors. The CPC-PVT with fins performs better than the flat plate PVT collector. Farshchimonfared et al. (2015) optimized the duct depth and air mass flow rate for a PVT air collector (different collector area and different length/width ration) linked to an air distribution system of a residential building in mild winter. The duct depth increases with increase in the collector area and length/width ratio.

The generic algorithm with multi-objective function was used to study (i) the thermal energy efficiency and exergy efficiency of glazed single channel PVT module (Singh et al., 2015a), (ii) the design parameter of single channel PVT air collector (Singh et al., 2015b) and (iii) the performance of dual channel PVT air collectors (Singh et al., 2016). It was concluded in these studies that generic algorithm is an efficient technique for optimization of efficiencies and design parameter. Also the dual channel PVT air collector performs better in comparison to the single channel PVT air collector. The dual channel bi-fluid PVT collector (Su et al., 2016; Jarimi et al., 2016) have been studied and concluded that water-water PVT collectors perform better than the water-air or air-air PVT collectors. Air-air PVT collector produces large quantity of hot air with high temperature.

In earlier literature the PVT air collectors fully covered by opaque or semitransparent PV modules have been studied theoretically and experimentally. The PVT air collector fully covered with semitransparent PV module produces nearly 60 °C outlet air temperature for a 0.605 m^2 collector area at 0.02 kg/s mass flow rate (Dubey et al., 2009b). The outlet air temperature can be increased by reducing the solar cell area and increasing the glazing area. The series connected partially covered PVT water collector (Shyam et al., 2015, 2016) has been studied theoretically and experimentally, but in earlier literatures performance of partially covered (by semitransparent PV module) series connected PVT air collector has not been investigated. The performance analysis of series connected PVT air collectors partially covered by semitransparent PV module is important as it give higher outlet temperature as compared to fully covered PVT collectors, also this system can be used where the instant use of thermal energy (during sunshine hours) is required e.g. solar crop drying and other drying industries. Optimization in terms of mass flow rate and number of collectors for partially covered PVT collectors is important because it can predict the desired outlet temperature and produced electrical energy for a particular application. Generation of electrical energy using solar energy makes the PVT collectors more viable for the remote locations of the developing countries like India where constant supply of grid electricity is not available. The PVT air collector can serve as one of the best options for solar drying of agricultural