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Exergy analysis of photovoltaic thermal (PVT) compound parabolic concentrator (CPC) for constant collection temperature mode

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ABSTRACT

In this communication, an attempt has been made to evaluate exergy of photovoltaic thermal compound parabolic concentrator (PVT-CPC) water collector system [case (i)] for constant collection temperature mode of operation. The performance of PVT-CPC water collector systems can be analyzed in two modes namely (i) constant mass flow rate and (ii) constant collection temperature. In the present analysis, an analytical expression for mass flow rate and electrical efficiency of PV module for partially covered PVT-CPC water collector system [case (i)] have been developed to determined the performance under constant collection temperature mode. Such system will be most useful for thermal space heating of buildings to conserve fossil fuel to save environment. The comparison of proposed system with fully covered PVT-CPC water collectors [case (ii)], conventional CPC water collectors [case (iii)] and partially covered PVT water collectors [case (iv)] have also been carried out for climatic condition of New Delhi. Based on computation, it has been found that for fully covered PVT-CPC water collector system [case (ii)] (a) at high operating temperatures, instantaneous thermal efficiency has lower value in comparison with constant mass flow rate condition; (b) at high concentration ratio ($C = 5$), higher operating temperature is achieved. The analytical expression of the electrical efficiency of the proposed system is also derived. An overall thermal and exergy analysis of PVT-CPC water collector system in terms of energy degraded into the environment and exergy destruction have also been carried out.

1. Introduction

For the conservation of conventional fossil fuels available to human kind, there is a need to search an alternative energy source locally available to meet our energy requirements. Basically, solar energy is directly responsible to produce renewable energy sources and indirectly for non-renewable energy sources (fossil fuel). One of easiest way to use solar energy is in the form of hot water through flat plate collector. It is also known that flat plate collectors (FPC's) give better performance under forced mode of operation in larger hot water system for industrial applications. For sustainable forced mode of operation of flat plate collector, photovoltaic thermal (PVT) flat plate collectors have been developed. There are lots of works carried out by many researchers in the area of photovoltaic thermal (PVT) flat plate collectors. However, there is a variation in operating outlet fluid temperature (T_{fo}) using such system (PVT-FPC) for a given mass flow rate. To achieve constant exit operating outlet fluid temperature (T_{oo}), the mass flow rate should be controlled by using appropriate temperature sensor for a known insolation (solar intensity). Sodha et al. (1981) have studied the performance of forced circulation solar water heating system with and without heat exchanger for constant collection temperature mode. Sinha and Tiwari (1992) investigated the thermal performance of commercial solar hot water system for constant delivery temperatures. It was reported that when constant delivery temperature increases then the time in which the system operates also reduces. In this direction the same concept was applied by Tiwari et al. (2009) for an exergy analysis of integrated photovoltaic thermal solar water heater under constant collection temperature modes and the results were also compared with constant flow rate mode. It was observed that the overall daily thermal efficiency of integrated photovoltaic thermal system (IPVTS) increased with the increase in constant mass flow rate and decreased with increase of constant collection temperature. Alta et al. (2010) have found that the thermal efficiencies of the finned air collectors were high as compared to air collector without fin. The irreversibility was found to be highest in air collector without

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Nomenclature

A	area (m^2)
A_a	total aperture area (m^2) ($A_a = A_{am} + A_{ac}$)
A_{am}	aperture area over PV module (m^2)
A_{ac}	aperture area over glazed portion (m^2)
A_r	total receiver area (m^2)
A_{rm}	receiver area covered by PV module (m^2)
A_{rc}	receiver area covered by glass (m^2)
b	breadth of receiver (m)
b_o	breadth of aperture area of glass (m)
c_f	specific heat of fluid (J/kg K)
C	concentration ratio, dimensionless
dx	elemental length (m)
$\dot{E}x$	exergy (kW h)
F'	flat plate collector efficiency factor
F_R	flow rate factor, dimensionless
h	heat transfer coefficient (W/m^2 K)
L_{rm}	length of receiver covered by PV module (m)
L_{rc}	length of receiver covered by glass (m)
L_r	total length of the aperture area (m)
L_{en}	energy loss (kW h)
L_{ex}	exergy loss (kW h)
PF_1	first penalty factor due to glass cover
PF_2	second penalty factor due to absorber/receiver plate
PF_c	penalty factor due to glass cover for the portion covered by glazing
I_t	total radiation (W/m^2)
I_b	beam radiation (W/m^2)
$\dot{m}_f$	mass flow rate of water in (kg/s)
T_{oo}	constant collection temperature (°C)
$U_{t,ca}$	overall heat transfer coefficient from solar cell to ambient through glass cover (W/m^2 K)
$U_{t,cp}$	overall heat transfer coefficient from solar cell to plate (W/m^2 K)
$U_{t,pa}$	total (top and bottom) overall heat transfer coefficient from plate to ambient (W/m^2 K)
U_{L1}	overall heat transfer coefficient from blackened surface to ambient (W/m^2 K)
η_o	efficiency at standard test condition ($I_t = 1000\ W/m^2$, $T_o = 25$ °C)
β_o	temperature coefficient of efficiency (K^{-1})

Greek letters

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

Subscript

a	ambient
c	solar cell
eff	effective
f	fluid
fi	inlet fluid
fo	outlet fluid
g	glass
m	module
p	plate

Abbreviations

PV	photovoltaic
CPC	compound parabolic concentrator
PVT	photovoltaic thermal
PVT-CPC	photovoltaic thermal compound parabolic concentrator

fins. Tiwari et al. (2011) have reviewed analytical work on PVT technology which includes an overall thermal performance, exergy analysis, energy matrices and uniform annual cost (una cost) analysis including constant collection temperature mode. Saidur et al. (2012) studied the detailed exergy analysis of solar energy applications namely solar photovoltaic, solar heating devices, solar water desalination system, solar air conditioning and refrigerators, solar drying process and solar power generation. They have observed that the highest exergy destruction was in solar collectors in most of the solar heating devices and solar air conditioning systems. Ceylan (2012) analyzed a temperature controlled (constant temperature mode) solar water heater by using the concept of energy (first law of thermodynamics) and exergy (second law of thermodynamics). It was experimentally observed that the temperature controlled solar water heater (TCSWH) and thermo-siphon water system for the control device set to 45 °C. An average energy efficiency of TCSWH thermo-siphon system was reported as 65% and 60% respectively. Later on, Mishra and Tiwari (2013) have extended the work of constant collection temperature for N-photovoltaic thermal (PVT) flat plate collectors connected in series. They concluded that for N-photovoltaic thermal (PVT) flat plate collectors connected in series, there was not much difference in overall performance for placing semi-transparent PV either above portion or below portion of flat plate collector (FPC) in any mode of operation. Recently, Ceylan et al. (2014) have seen the effect of temperature controlled cooling on performance of photovoltaic module solar collector. It was observed that electrical efficiency with cooling effect has maximum value of 13% in comparison with electrical efficiency without cooling as expected.

Bouadila et al. (2014) studied energy and exergy analyses of solar air heaters with and without latent heat storage materials. They reported that the daily energy and exergy efficiencies varied between 32–45% and 13–25% respectively. Further, exergy analyses of solar photovoltaic thermal (PVT) water collector with and without collection cum storage were carried out by Sobhnamayan et al. (2014) and Ziapour et al. (2014). The PVT-CPC system has a dual advantage firstly thermal energy and electricity is produced and secondly the photovoltaic cell area decreases which leads to a decrease in system cost. Nowadays in most of the industries the requirement of hot water at a constant temperature is growing in abundance. Therefore, in this paper, an attempt has been made to an overall energy and exergy analyses of photovoltaic thermal (PVT) compound parabolic concentrator (CPC) under constant collection temperature mode which can be utilized for industrial applications. These analyses have been carried out for the climatic and design parameters used by Atheaya et al. (2015). Comparison of partially covered PVT-CPC water collector system [case (i)] has also been made with fully covered PVT-CPC water collector system [case (ii)], conventional CPC water collector system [case (iii)] and partially covered PVT water collector system [case (iv)].

2. Photovoltaic thermal compound parabolic concentrator system

The photovoltaic thermal compound parabolic concentrator considered in this present study [case (i)] was proposed by