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Exergy and thermoeconomic optimization of a water-cooled glazed hybrid photovoltaic/thermal (PVT) collector

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Abstract

Hybrid photovoltaic/thermal collectors (PVT) consist of common photovoltaic modules cooled by a suitable fluid, and convert solar radiation simultaneously into both thermal and electric energy. The heat transfer between PV cells and fluid allows to reduce the temperature of the PV cells; this improves the electrical efficiency, but also makes available low-grade heat for specific applications. As a consequence, PVT modules show a very interesting overall energy efficiency.

In this paper, the Second Law analysis of a water-cooled PVT collector is presented, based on simulations. The study also discusses a crucial problem for the optimal exploitation of this technology: the electricity production from PV cells is favoured by low temperatures, whereas the usability of the thermal energy gets higher at high temperatures.

The paper demonstrates that, for any operating condition, it is possible to calculate an optimum water inlet temperature that maximizes the total exergy generated by the system. The optimum temperature falls within the range commonly occurring in solar thermal systems, and can be achieved in practice through a simple control-command system. Finally, a thermoeconomic analysis is carried out to define the price of the thermal energy produced by the PVT collector, as a function of its exergy content.

Keywords: PVT collectors; Energy efficiency; Thermodynamic optimization; Thermoeconomics

1. Introduction

Hybrid photovoltaic/thermal (PVT) collectors are devices that convert solar radiation simultaneously into thermal and electric energy. This results in a higher overall solar conversion rate per unit surface area, if compared to that provided by the separate production of electric and thermal energy through common PV and thermal collectors placed next to each other.

Basically, PVT collectors consist of a thin plate made of highly conductive material, on top of which the PV cells are inserted by lamination; here, solar radiation is collected and partially converted into electricity. In the same time, the circulation of a fluid (usually air or water) against the absorber plate is allowed: this fluid, while removing the excess heat from the PV cells, lowers their temperature and potentially improves their electrical efficiency; in the meanwhile, low-grade heat can be made available for appropriate uses.

However, since PVT collectors are a quite recent technology, many issues concerning their design, the market potential and possible barriers for their practical application are still being investigated, as witnessed by the copious number of papers recently published about this topic. The main findings are collected in some recommendable review

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Nomenclature

a	external side of the channel (m)	T_{in}	inlet temperature (K)
A_c	overall surface area of the collector (m^2)	T_m	mean thermodynamic temperature (K)
A_p	overall surface area of the absorber plate (m^2)	T_{out}	outlet temperature (K)
A_{PV}	surface area covered by PV cells (m^2)	T_p	temperature of the absorber plate (K)
c_{pp}	specific heat of the absorber plate (J/(kg K))	T_0	reference temperature (dead state) (K)
c_{pw}	specific heat of water (J/(kg K))	T^*	reduced temperature (m^2 K/W)
C_{el}	unit cost of electricity (€/kW h)	U_L	overall heat transfer coefficient of the absorber plate (W/(m^2 K))
$C_{t,en}$	unit cost of thermal energy (€/kW h)	u_w	wind velocity over the glass cover (m/s)
$C_{t,ex}$	unit cost of thermal exergy (€/kW h)	u_c	water velocity inside the channel (m/s)
C_0	annual capital cost (€)	W	tube spacing (m)
CRF	capital recovery factor	$\dot{Z}$	annual capital cost rate (€/year)
D_{eq}	equivalent diameter for the square tube (m)	α_p	short-wave absorptance of the absorber plate
$\dot{e}_{sol}$	exergy rate of the solar radiation per unit surface (W/m^2)	β	tilt angle on the horizontal plane (°)
$\dot{E}_{el}$	electric exergy rate (W)	δ_c	thickness of the channel, m
$\dot{E}_Q$	thermal exergy rate (W)	δ_{ins}	thickness of the insulating layer, m
F	fin efficiency	δ_p	thickness of the absorber plate, m
H	width of the collector (m)	ε_g	thermal emissivity of the glazing
h_{cc}	internal convective heat transfer coefficient for the channel (W/(m^2 K))	ε_p	thermal emissivity of the absorber plate
		η	overall energy efficiency of the collector
h_{cg}	external convective heat transfer coefficient for the glazing (W/(m^2 K))	η_{el}	electric energy efficiency of the collector
		η_{PV}	electrical efficiency of the PV cells
h_{in}	specific enthalpy for the inlet flow (J/kg)	η_{STC}	electrical efficiency at standard test conditions
h_{out}	specific enthalpy for the outlet flow (J/kg)	η_t	thermal energy efficiency of the collector
i	annual interest rate, %	λ_c	thermal conductivity of the channel (W/(m K))
I_{sol}	solar irradiance (W/m^2)	λ_{ins}	thermal conductivity of the insulating layer (W/(m K))
L	length of the collector (m)		
$\dot{m}_{ws}$	water mass flow rate per unit surface ((kg/h)/m^2)	λ_p	thermal conductivity of the absorber plate (W/(m K))
n	expected lifespan of the PVT collector (years)	λ_w	thermal conductivity of water (W/(m K))
n_{PV}	number of PV cells	μ	temperature coefficient of the PV cells (°C^{-1})
Nu	Nusselt number	ξ	overall exergy efficiency of the collector
P_{el}	electric power (W)	ξ_{el}	electrical exergy efficiency of the collector
PF	packing factor	ξ_t	thermal exergy efficiency of the collector
$\dot{Q}_{abs}$	absorbed thermal power (W)	ρ_{gd}	short-wave reflectance of the glazing for diffuse radiation
$\dot{Q}_L$	heat losses to the environment (W)		
$\dot{Q}_t$	overall useful thermal power (W)	σ	Stefan-Boltzmann constant (W/(m^2 K^4))
$\dot{Q}_w$	useful thermal power per single fin (W)	τ_g	short-wave transmittance of the glazing
Re_{Deq}	Reynolds number	ψ	latitude (°)
s_{in}	specific entropy for the inlet flow (J/(kg K))	ψ_s	conversion coefficient for the exergy of solar radiation
s_{out}	specific entropy for the outlet flow (J/(kg K))		
t	time (s)		
T_a	outdoor air temperature (K)		

papers (Charalambous et al., 2007; Arif Hasan and Sumathy, 2010; Zhang et al., 2012; Moradi et al., 2013; Arcuri et al., 2014). Here, the effects of the main design parameters on the collector performance are investigated, e.g. the type of fluid, the mass flow rate, the number of covers and the shape of the absorber plate.

Another key point emerging in the literature is the role of the fluid temperature. Indeed, if one aims at producing hot water ready for technical applications, it should be necessary to operate at least around 40–50 °C; however, such a temperature might penalize the electric performance of the PV cells. On the contrary, lower temperatures would allow better electrical efficiency, but they would also affect the usefulness of the recovered heat (Tiwari, 2002).

To understand how much useful is the heat, as a function of the temperature at which it is available, the most