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A coupled optical-thermal-electrical model to predict the performance of hybrid PV/T-CCPC roof-top systems

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A B S T R A C T

A crossed compound parabolic concentrator (CCPC) is applied into a photovoltaic/thermal (PV/T) hybrid solar collector, i.e. concentrating PV/T (CPV/T) collector, to develop new hybrid roof-top CPV/T systems. However, to optimise the system configuration and operational parameters as well as to predict their performances, a coupled optical, thermal and electrical model is essential. We establish this model by integrating a number of submodels sourced from literature as well as from our recent work on incidence-dependent optical efficiency, six-parameter electrical model and scaling law for outdoor conditions. With the model, electrical performance and cell temperature are predicted on specific days for the roof-top systems installed in Glasgow, Penryn and Jaen. Results obtained by the proposed model reasonably agree with monitored data and it is also clarified that the systems operate under off-optimal operating condition. Long-term electric performance of the CPV/T systems is estimated as well. In addition, effects of transient terms in heat transfer and diffuse solar irradiance on electric energy are identified and discussed.

1. Introduction

Flat-plate photovoltaic/thermal (PV/T) hybrid solar collectors, first-time proposed in 1978 [1] and later tested by Ref. [2], have been developed over the years for efficient solar energy utilization – excellent reviews of this subject were provided in Refs. [3,4]. In Ref. [5], a Solarex MSX60 polycrystalline flat-plat PV module was integrated with a heat collecting plate to form a PV/T module and both the electrical and thermal performances of the module were tested. The module showing its primary-energy saving efficiency exceeds 0.6 in comparison with a pure solar thermal collector. Hourly and monthly electrical and thermal performances of a PV/T array were predicted under Cyprus [6] and Greece [7] climate conditions by using TRNSYS software. Various design methods were discussed in Ref. [8] to improve the electrical and thermal performances of a flat-plat PV/T hybrid air collector. Effects of water flow rate and packing factor on the energy performance of a façade-integrated PV/T system were predicted and clarified by using a lumped thermal model [9].

The overall performance of a PV/T collector with and without glass cover was also analysed in Ref. [10] and a PV/T collector with glass cover having a better performance was identified. A thermal model of a UK domestic PV/T system was established in Ref. [11], and the packing factor of solar cells and water flow rate was optimized. A full unsteady, 3D numerical thermal model was developed in Ref. [12] to investigate the hourly and monthly electrical and thermal performances of a flat-plat PV/T system, and it was shown that the use of time-averaged climate can lead to an overestimation of the thermal performance.

To improve overall performance of flat-plate PV/T collectors, a PV/T roof-top system with crossed compound parabolic

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Nomenclature

a_1, a_2, a_3 coefficients in Eq. (1) respectively related to glass reflectance, absorptance of PV cells and absorber, PV cell parking/active area
A_c collecting area of CPV/T module
A_{cell} area of all the cells in a CPV/T module
A_h cross-sectional area of flow channels in a heat exchanger, m^2
b gap/spacing between two plates in a finned heat exchanger, m
B^j control function of mass flow rate between two segments of water body in a tank in Eq. (12)
c_1, c_2 empirical constants in Eq. (A2)
C specific heat capacity of a part of CPV/T module, J/(kg K)
C_{fj} water specific heat capacity in the j^{th} segment of water body in a storage tank, $j = 1, 2..., N_t$, J/(kg K)
CR concentration ratio of a CCPC module
d ratio of the diffuse irradiance over the global irradiance on a CPV/T module
E_g band-gap energy of PV cell, eV
E_{PV} instant electrical power generated by PV cells per unit collecting area, W/m^2
g gravitational acceleration, $g = 9.81$ m/s^2
h_{bf} forced convection heat transfer coefficients on the wall of a heat exchanger next to the back cover, W/(m^2 K)
h_{con} free convection heat transfer in the cavity of between the glass cover and the PV cells in a flat PV/T module or in a CCPC cavity, W/(m^2 K)
h_{ga} heat transfer coefficient to account for the radiative heat losses of the top glass cover to the sky plus the wind convection heat transfer coefficient, W/(m^2 K)
h_{pb} radiative heat transfer coefficient of the absorber plate to the back cover, W/(m^2 K)
h_{pg} radiative heat transfer coefficient plus natural convection heat transfer coefficient of the absorber to the glass cover, W/(m^2 K)
h_{pf} forced convection heat transfer coefficients on the wall of a heat exchanger next to the absorber, W/(m^2 K)
h_{sg} radiative heat transfer coefficient plus natural convection heat transfer coefficient of the PV cells to the glass cover, W/(m^2 K)
h_t total heat transfer coefficient between the tank wall and the outside air, W/ K
h_{wind} convection heat transfer coefficient due to wind, W/(m^2 K)
H fin height, m
I current of PV cells/modules, A
I_d diode reversal saturation current, A
I_{ph} photocurrent of PV cells/modules, A
k air/water thermal conductivity, W/(m K)
k_{fin} fin thermal conductivity
L length of flow channels/fins in a heat exchanger, m
m optical gain coefficient of a CCPC module
$\dot{m}_f$ water mass flow rate through a heat exchanger, kg/s
$\dot{m}_{sj}$ mass flow rate between two segments of water body in a tank in Eq. (12), kg/s
M mass of a part of CPV/T module, kg/m^2
n diode quality factor of PV cells/modules
n_1, n_2 empirical powers in Eq. (A2)
N_t total number of segments of water body in a storage tank, $N_t = 10$
Nu Nusselt number of natural convection heat transfer coefficient, $\mathrm{Nu} = h_{con}b/k$
Nu_b Nusselt number of fin channels, $\mathrm{Nu}_b = h_{fin}b/k$, h_{fin} will be either h_{pf} or h_{bf} in Eq. (1) or (1a)
Nu_i ideal Nusselt number of fin channels, defined in Eq. (A4)
Pr fluid Prandtl number, $\mathrm{Pr} = \nu/\tau$
q electron charge, $1.60217646 \times 10^{-19}$C
Ra Rayleigh number of the air between the plates, $\mathrm{Ra} = g\beta'(T_{hot} - T_{cold})b^3/\nu\tau$
Re_b Reynolds number, $\mathrm{Re}_b = Ub/\nu$
Re_b^* Reynolds number of fin channels, $\mathrm{Re}_b^* = \mathrm{Re}_b(b/L)$
R_g reflectance of top glass cover
R_s lumped series resistance of PV cells/modules, Ohm
R_{sh} shunt resistance of PV cells/modules, Ohm
S solar irradiance, W/m^2
t time, s
T Temperature, °C
T_a ambient temperature, °C
T_{cold} the lowest temperature of two plates, K
T_{fi} water temperature at the inlet of the first heat exchanger of CPV/T module, °C
T_{fij} water temperature at the inlet of the first heat exchanger of CPV/T module in the j^{th} month a year, °C
T_{fo} water temperature at the outlet of the last heat exchanger of CPV/T module, °C
T_{fout} temperature of water at the outlet of the last heat exchanger of a CPV/T module, °C
T_{hot} the highest temperature of two plates, K
T_j water temperature in the j^{th} segment of water body in a storage tank, $j = 1, 2..., N_t$
T_{sky} Temperature of the sky, °C
U mean fluid velocity in fin channels, m/s
v_{wind} wind speed, m/s
V output voltage of PV cells/modules, V
V_{fj} water volume in the j^{th} segment of water body in a storage tank, $j = 1, 2..., N_t$, m^3

Greek symbols
α absorption coefficient of top glass cover or PV cell or absorber
β tilted angle of a CPV/T module, °
β' volumetric coefficient of expansion of air
γ experimental incidence angle modifier coefficient
δ thickness of fin, mm
ε emissivity of a part of CPV/T module
η_{opt} optical efficiency of a CCPC module
θ solar beam incidence angle on a CPV/T module, °
θ_{eff} effective incidence angle of diffuse irradiance, °
κ Boltzmann constant, $1.38065031 \times 10^{-23}$J/K
μ temperature coefficient of short circuit current, A/K
ν kinematic viscosity of fluid, m^2/s
ρ_{fj} water density in the j^{th} segment of water body in a storage tank, $j = 1, 2..., N_t$, kg/m^3
σ Stefan-Boltzman constant, 5.670367×10^{-8} kg s^{-3} K^{-4}
τ thermal diffusivity of air, m^2/s