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Multi-objective optimization of hybrid photovoltaic–thermal collectors integrated in a DHW heating system

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ABSTRACT

A mathematical model for making quantitative and qualitative predictions regarding the performance of water-cooled photovoltaic/thermal collectors integrated with a building domestic hot water preparation system has been developed. A genetic algorithm has been applied to the model in order to simultaneously find optimal design parameters affecting photovoltaic/thermal collectors' feasibility. For all formulated problems, Pareto optimal sets of conflicting solutions are obtained giving the designer information on the trade-off relationships between solutions.

1. Introduction

Solar cells act as good heat collectors in hybrid photovoltaic–thermal (PV/T) systems and can be integrated and optimized with buildings for the simultaneous use of renewable DC power and heat. For the last forty years, many innovative PV/T systems and products have been documented. The academic and professional evaluation of these innovations, a range of theoretical models and validated experimental data are reviewed by Charalambous et al. [1] and later by Zondag [2].

PV/T systems' practical implementations are still limited at present mostly to experimental applications. A PV/T collector is only a part of a given energy application. If a domestic hot water (DHW) preparation system is chosen, the systems include thermal storage, piping, pumping unit and control equipment. Building-integrated applications (BiPVT) have been reviewed by Bazilian and Prasad [3]. A detailed review of thermosyphon applications, PV/T integrated heat pumps and concentrator-type PV/T has been carried out by Chaw [4].

Even though the presented research is restricted to water-cooled PV/T technology, it nonetheless remains a broad area of research and a number of technical details and applications have been omitted to be able to give focused overview.

As a summary, the following are the contribution of the present paper:

- A procedure for simultaneously analyzing performance parameters of a PV/T system connected with a DHW heating system using Metaheuristics. The literature for the last 40 years does not provide for a procedure that simultaneously finds optimal performance parameters of PV/T models and systems.
- Multi-objective optimization of PV/T with a DHW heating system is performed with solar cells effectiveness as one objective vs. various conflicting objectives like maximization of thermal efficiency, minimization of backup hot utility, minimization of pressure drop in the tubes and minimization of initial investment on the system. These problems have not been reported in literature.
- Fluid mass-flow rate, solar cells aspect ratio, model length, air gap, storage tank volume and number of PV/T collectors are chosen as design variables. These design parameters have not been selected as a group to be optimized in previous research in the subject.

Two PV/T models are studied, one with a front glass cover and one without a glass cover. The authors first apply a thermal procedure which yields performance parameters separately. Secondly, the thermal model is adapted in order to apply the elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II). The NSGA-II is described in details by its author Deb in Ref. [5]. The predicted results from applying multi-objective optimization on PV/T models

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Nomenclature

A	surface area, m^2
c	specific heat, J/kg/K
D	diameter of water pipe, m
E	DC power, W
F	control parameter
h	heat transfer coefficient W/m^2/K
G	solar radiation density, W/m^2
I	initial investment, €
k	thermal conductivity, W/m/K
L	length, m
m	mass, kg
M	number of objectives
$\dot{m}$	mass-flow rate, kg/s
Nt	number of water tubes, number of individuals
Nu	Nusselt number
Pr	Prandlt number
Q	heat flux, W
R	thermal resistance, K/W
Re	Reynolds number
R_g	refractive index of glass cover
r_c	ratio of solar cell area to aperture area
(ρV_c)	lumped heat capacity, J/K
SF	solar factor
T	temperature, °C
t	time, s
V	volume, l
V_s	number of generations
W	width, m
z	thickness, cm

Greek letters

α	absorptance
β	temperature coefficient, 1 K
ε	emissivity
Λ	extinction coefficient of glass cover, 1 m
η	efficiency, distribution index
ρ	density, reflectance
τ	transmittance
θ	angle of incidence, angle of refraction of direct beam,°
Θ	absolute temperature, K
$(\tau\alpha)$	effective absorptance
σ	Stefan–Boltzmann constant, W/m^2/K^4
ψ	pipe friction coefficient
ξ	hydraulic resistance coefficient

Subscripts

a	air
ad	adhesive layer
c	solar cell, collector, crossover
e	electrical, environment
g	glass cover
h	hydraulic
i	insulation material
m	mutation
o	outer
p	absorber plate
r	radiation, reference
s	stratification section
sys	system
t	tube, tank
ut	utility
w	water
0	inlet
1	incident beam
2	outlet, refracted beam

is in good agreement with the first thermal model. These results are obtained in one single run of the model.

2. Analytical models for PV/T collectors' design

2.1. Temperature influence on PV module efficiency

The best known model for photovoltaic module efficiency as a function of temperature is given by Evans [6], with the following experimental equation:

$$\eta_c = \eta_r[1-\beta(T_c - T_r)] + \gamma \log G; \tag{1}$$

where η_r is the reference module efficiency at a PV cell temperature T_r of 25 °C and at a reference solar irradiance G on the module. T_c is the PV cell temperature. γ and β are, respectively, the solar irradiance and temperature coefficients for the PV module. γ and β depend on the material used for the PV cells. Evans [6] suggested for silicon $\beta = 0.00488\ \mathrm{C}^{-1}$ and $\gamma = 0.12$. In this research the assumption is that the term $(\gamma \log G) = 0$. This assumption is in line with all other researchers [1–4,6,7], who studied similar PV temperatures.

2.2. The thermal model

One of the most common ways of using solar energy is for DHW preparation. Among all the interacting parts of a DHW system; two main components can be highlighted as the most important regarding system efficiency: the solar collectors and the storage tank (Fig. 1). In order to investigate the feasibility of PV/T technology connected with a DHW system, a thermal model of the system has been developed and an optimization procedure has been applied to the model.

Thermal models for stand alone PV/T collectors' performance evaluation have been presented in literature [7–10]. The models explain the essential energy flows by conduction, convection and radiation throughout a serial assembly of many one-dimensional elementary layers.

The thermal model we present searches for optimal daily PV efficiency, thermal efficiency and energy gain for the PV/T collectors connected with a DHW heating system to find optimal designs (optimal flow rate, aspect ratio, optimal collector's length, optimal air gap, hot water tank's capacity and number of collectors).

2.2.1. PV/T collector model with glass cover

Thermal behaviour of the entire collector can be well defined from the heat transfer analysis in the vicinity of a single water tube. Fig. 2 is the schematic, presented in the resistance network's analogy, of the collectors' cross section along the Z-axis perpendicular to each water tube. The thermal analysis is derived based on this model.

Transparent front cover

$$(\rho Vc)_g \frac{dT_g}{dt} = h_{ag}A_{ag}(T_a - T_g) + h_{eg}A_{eg}(T_e - T_g) + h_{gc}A_{gc}(T_c - T_g) + Q_g; \tag{2}$$

Photovoltaic cell

$$(\rho Vc)_c \frac{dT_c}{dt} = h_{gc}A_{ag}(T_g - T_c) + h_{cp}A_{pc}(T_p - T_c) + Q_c; \tag{3}$$