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Numerical model for the thermal yield estimation of unglazed photovoltaic-thermal collectors using indoor solar simulator testing

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ABSTRACT

It is a common practice to test solar thermal and photovoltaic-thermal (PVT) collectors outdoors. This requires testing over several weeks to account for different weather conditions encountered throughout the year, which is costly and time consuming. The outcome of these tests is an estimation of the thermal performance characteristics of the collector. Collector performance parameters can be derived with less effort by indoor testing under a solar simulator. However, in case of unglazed PVT collectors the thermal and the electrical performance is affected by two phenomena-additional long wave radiation (3000 nm and greater) due to emissions and reflections from the high temperature artificial sky, and an energy content of the PV spectrum (300–1100 nm) that differs from the global solar spectrum (300–2500 nm). These differences from the reference AM 1.5 solar spectrum lead to errors in the estimation of collector thermal and electrical performance. Therefore, results of indoor performance tests must be corrected to obtain the output of an unglazed PVT collector in real outdoor environment.

In this paper a method is proposed to estimate the real thermal performance of unglazed PVT collectors, by using a compact indoor solar simulator testing in combination with a detailed steady state numerical PVT collector model. The numerical model takes into account the physical and spectral attributes of the solar simulator and is used to correct for the unwanted phenomena to derive the actual outdoor collector performance. The resulting numerical model also offers detailed understanding of the collector and can therefore be used to optimise the design of the collector. Furthermore, this model is used to derive thermal performance characteristics of the unglazed PVT collector as defined by solar thermal testing standards, which can be used in system simulation tools (E.g. TRNSYS models) to obtain annual collector and system yields.

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1. Introduction

Use of solar energy in the building sector is still limited due to several challenges, namely —limited roof area; high costs of solar thermal collectors when compared with conventional alternatives; and the lack of aesthetic integration into building roofs (Stryi-Hipp et al., 2012). PVT (abbreviated for combined photovoltaic-thermal) collectors can tackle these issues - by providing aesthetic homogeneity to the roof and using the roof area more effectively; and by reducing balance of system and installation costs, as a result of combining a PV panel and a solar thermal collector into a single module. A PVT panel/collector is a panel in which either PV cells are directly laminated on to a thermal absorber; or a PV module is placed on top of a thermal absorber, to produce heat and electricity from the same irradiated area. PVT collectors promise clear advantages over the combination of PV panels and solar thermal collectors.

Zondag (2008), Hasan and Sumathy (2010), Tyagi et al. (2012), Aste et al. (2014), Al-Waeli et al. (2017), etc., have reviewed the historical evolution of PVT collectors, by studying experimental work, field studies, qualitative performance evaluation, numerical models and analytical studies carried out by different researchers in past decades.

Over the years, a number of field testing and experimental studies on PVT collectors have been performed across the world (Suzuki and Kitamura, 1979; Vries et al., 1997; Tripanagnostopoulos et al., 2001; Huang et al., 2001; Bakker et al., 2002, 2004; Sadamoto et al., 2003; He et al., 2006; Robles-Ocampo et al., 2007; Assoa et al., 2007; Chow et al., 2009; Dupeyrat et al., 2011b; Ceylan

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Nomenclature

Symbol	Description (Unit)
A	gross surface area of the collector (m^2)
A_s	area of a collector segment (m^2)
b_1	heat loss coefficient at zero reduced temperature (W/m^2 K)
b_2	wind dependence of heat loss coefficient (W s/m^3 K)
b_u	collector efficiency coefficient (wind dependence) (s/m)
C_p	specific heat of circulating fluid (J/kg K)
D	outer diameter of the tube (m)
d_{cavity}	diameter of the U-shaped cavity (m)
D_h	hydraulic diameter of the channel (m)
F_G	function describing the dependency of the PV laminate output on the incident irradiance (–)
F_{ij}	view factor from surface i to surface j (–)
F_T	function describing the dependency of the PV laminate output on the temperature of solar cells (–)
G	global irradiance normal to the collector surface (W/m^2)
G^*	Net irradiance normal to the collector surface, corrected for the long wave radiation (W/m^2)
Gr	Grashof number (–)
I	output current of the PVT collector (A)
J	radiosity of the surface (W/m^2)
k	heat conductivity of a material (W/m K)
k_{air}	heat conductivity of air (W/m K)
l	length of the segment (m)
$\dot{m}$	mass flow rate of the circulating fluid (kg/s)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
Q	energy flow (W)
Ra	Rayleigh number (–)
Re	Reynolds number (–)
T	temperature (K)
T_{red}	reduced temperature (K m^2/W)
U	heat loss coefficient (W/m^2 K)
V	output voltage of the PVT collector (V)
$\dot{V}$	volume flow rate of the circulating fluid (m^3/s)
W	centre to centre distance between the tubes in the collector (m)
β	temperature coefficient for maximum electrical power at a given cell temperature (–)
δ	thickness of a material layer in the PVT collector (m)
ϵ	emissivity of the surface (–)
η_0	zero loss thermal efficiency at T_{red} = 0 (–)
$\eta_{0,b}$	peak collector efficiency (–)
η_E	electrical efficiency of the PVT collector (–)
η_{STC}	electrical efficiency of the PV laminate under standard test conditions (–)
η_T	thermal efficiency of the PVT collector (–)
ν	kinematic viscosity of a fluid (m^2/s)
σ	Stefan Boltzmanns constant (W $m^{-2}K^{-4}$)
$\langle\tau\alpha\rangle$	transmission-absorption factor for the PVT collector (–)

Subscripts

abs	flat absorber section
a	ambient air
back	back insulation
bot	bottom glass surface
cell	solar cells
con	conduction
conv	convection
curv	U-shaped curved absorber section
el	electricity
f	circulating fluid
gr	ground
g	glass surface
ins	back insulation
ir,net	net absorberd radiation
m	mean
mpp	maximum power point
rad	radiation exchange between the panel and the surroundings
room	refers to the experiment room
sky	outdoor/artificial sky
top	glass top surface
tube,in	inner surface of the tube carrying the circulating fluid

et al., 2014; Rommel et al., 2014; Cremers et al., 2015; Aste et al., 2015; Rommel et al., 2015), etc.

In addition to the field testing, in recent years a number of studies involved indoor performance testing of PVT collectors under a solar simulator, testing both air and liquid PVT collectors (Solanki et al., 2009; Dupeyrat et al., 2011a; Agrawal et al., 2012; Dupeyrat et al., 2014; Fudholi et al., 2014), etc. In each of these studies, the solar simulator either consisted of halogen lamps, or measurement requirements were based on the ISO 9806-1 (ISO 9806, 2013) or EN 12975-1 (BS EN 12975-1, 2006) testing procedure, which only specify the maximum non-uniformity (below 15%) of irradiance over the test surface. Details of the spectral distribution of these solar simulators have not been mentioned in many of these studies. Currently, there are a few manufacturers of solar simulators complying with both PV and solar thermal testing standards.

On the modelling of PVT collectors, various numerical models have evolved in time. Bergene and Løvvik (1995) created a detailed physical model of a sheet and tube PVT collector, incorporating the heat transfer in the collector through conduction, convection and radiation, as well as temperature dependent power generation. This model was based on the model for solar thermal collectors by Duffie and Beckman (1991). Vries (1998) presented dynamic as well as steady state numerical models for sheet and tube PVT collectors. He showed that the steady state model while not accurately representing the transient behaviour of a PVT collector, can closely estimate the total yield over a day or over a year, and it is less computation intensive. Further improving this steady state model, Zondag et al. (2003) presented theoretical models for 9 different PVT designs and evaluated them with respect to each other. Santbergen et al. (2010) used the numerical model presented by Zondag to simulate a domestic hot water system for a single family house and estimated the annual yield of the system. Recent work on PVT modelling has been done by Rejeb et al. (2015), investigating the effect of meteorological, design and optical parameters on the performance of the PVT collector using a numerical dynamic simulation model. Hocine et al. (2015) also developed a numerical simulation model by adapting the Hottel-Whiller model (1958) and making corrections to the heat loss coefficients. Aste et al. (2015) used a dynamic simulation model similar to the one proposed by Zondag, where they made some further corrections to the PV efficiency equation; and modelled the PV sandwich (PV laminate bonded with the roll-bond absorber) as a single temperature node.

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