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Thermal modeling and experimental evaluation of five different photovoltaic modules integrated on prototype test cells with and without water flow

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ABSTRACT

An analytical model of temperature dependent electrical and thermal efficiency of mono-crystalline (m-Si), polycrystalline (p-Si), amorphous silicon thin film (a-Si), cadmium telluride thin film (CdTe) and copper indium gallium selenide (CIGS) photovoltaic modules integrated on five prototypes identical insulted test cells is developed with and without surface water flow. This model helps in ascertaining the influence of temperature on their performance of building integrated photovoltaic-thermal (BiPVT) system. The theoretically calculated results are experimentally validated in outdoor ambient environment. The electrical & thermal efficiencies are calculated for both high and low mass flow rate of water, $\dot{m}_w$. Daily average electrical efficiency of photovoltaic modules; m-Si, p-Si, a-Si, CdTe and CIGS with and without water flow are found to be 12.30%, 10.98%, 6.08%, 6.60% and 7.71%, and 11.41%, 10.30%, 5.86%, 6.26% and 6.99% respectively. In constant room temperature mode, variation in mass flow rate of water, $\dot{m}_w$ is also evaluated. Overall thermal efficiency and overall exergy for all photovoltaic modules in both cases are also calculated. The characteristic equations of photovoltaic modules integrated on test cells are also developed for both cases.

1. Introduction

Photovoltaic cell is an energy conversion device and it has a threshold solar irradiance (photon energy) corresponding to energy gap beyond which no electron-hole pair generate instead dissipate their energy in heat forms [1,2]. Photovoltaic cell has the capability to convert about 6–19% of incoming solar irradiance into electricity depending upon types of photovoltaic cell technology and operating conditions. Almost more than 50% of incident solar irradiance goes waste and is converted into heat that leads to rise in photovoltaic cell operating temperature of about 50 °C above ambient temperature [3,4]. Hence, the electrical yields drop (decrease in electrical efficiencies) and permanent structural damage due long duration thermal stress are some undesirable consequences faced by photovoltaic modules [5]. The use of coolant as a fluid stream like air/water helps in cooling down photovoltaic module, it enhances electrical output and with proper design to reuse the extracted heat by coolant are the basic incentives towards advance in photovoltaic-thermal hybrid technology [6]. Here, both natural and forced circulation helps in reducing operating temperature of photovoltaic module and the simultaneous cooling of the photovoltaic module attains acceptable electrical efficiency coupled with heat extraction devices to achieve increased overall efficiency [7–10]. Since the photovoltaic-thermal concept was introduced, several researchers have conducted experimentation and numerical calculation aiming higher overall energy efficiency [11,12]. Some significant characteristics of photovoltaic-thermal system include dual nature like electricity and thermal output, flexibility towards using as a Building integrated photovoltaic-thermal (BiPVT) application, and use of heat output in both heating and cooling (desiccant cooling) suitable for domestic application [13–15]. Initially, the glazed collector using both air and liquid type fluid got considerable attention followed by an unglazed photovoltaic collector coupled with a heat pump getting significant focus [16,17]. Photovoltaic-thermal water and air based systems are most commonly used that employ water and air as a working fluid respectively, wherein, former being more efficient due to high heat conductivity/capacity [18,19,8,20–25]. However, water based system required some extensive modification to enable water tight and corrosion free structure, whereas, in natural or forced mode in air based photovoltaic-thermal through air channel on rear, top or both surfaces of photovoltaic is a simplest way to extract heat [26,27]. As far as heat extraction process is concerned, the efficacy of photovoltaic-thermal systems depends upon the type of photovoltaic technology used. Mono-

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Nomenclature

a	aperture area of water opening through the tube (m^2)
A_m	area of photovoltaic module (m^2)
A_t	area of inside wall surface of test cell (m^2)
ARC	alternating reference condition
B	breadth of photovoltaic module (m)
C	specific heat (J/kg K)
F_R	heat removal factor, dimensionless
h	heat transfer coefficient (W/m^2 K)
FF	fill factor, dimensionless
h_{tw}	heat transfer coefficient from water to ambient (W/m^2 °C)
h_{ew}	evaporative heat transfer coefficient from water to ambient (W/m^2 K)
h_{cw}	convective heat transfer coefficient from water to ambient (W/m^2 K)
h_{rw}	radiative heat transfer coefficient from water to ambient (W/m^2 K)
$I(t)$	incident solar intensity (W/m^2)
k	thermal conductivity (W/m K)
l	thickness (m)
L	length of photovoltaic module (m)
$\dot{m}_w$	mass flow rate of water (kg/s)
M_r	mass of air inside test cell (kg)
$\dot{Q}_u$	rate of useful thermal energy (W)
t	time (hr)
T	temperature (°C)
U_L	overall heat transfer coefficient ((W/m^2 K))
U_{ma}	an overall heat transfer coefficient from module to ambient through glass cover (W/m^2 K)
U_{mr}	an overall heat transfer coefficient from water/module to inside of test cell (W/m^2 K)
U_t	an overall heat transfer coefficient from inside of test cell to ambient (W/m^2 K)
U_{mw}	an overall heat transfer coefficient from module to water through glass cover (W/m^2 K)
R_e	reflectivity
R_{el}	Reynolds number
P_r	Prandtl number
P	pressure (pascal)
I_{sc}	short circuit current (A)
I_{sc}	short circuit current at STC (I(t) = 1000 W/m^2 and T_o = 25 °C) (A)
I_{mp}	module current at MPP (A)
V_{oc}	open circuit voltage (V)
V_{oc}	open circuit voltage at STC (I(t) = 1000 W/m^2 and T_o = 25 °C) (V)
V_{mp}	module voltage at MPP (V)
P_m	power generate by module (W)
$P_{m,o}$	power generate by module at STC (I(t) = 1000 W/m^2 and T_o = 25 °C) (W)
v, V	air velocity (m/s)(front and back surface)
ϑ_w	velocity of water (m/s)
ν	kinematic viscosity of water

Subscripts

1/2	case 1/2
a	ambient, air
arc	anti-reflective coating
ARC	alternative reference condition
b	tedlar polymer layer
ec	ethyl vinyl acetate (EVA) layer
th	thermal
i	inlet, insulation fitted in test cell
over,ex	overall exergy
over,th	overall thermal
m	module
r	test cell room
e	effective
g	glass
Gi	glass covering
PV	photovoltaic module
rm	rear metal contact
w	water, wood

Greek symbols

α_c	absorptivity of photovoltaic modules/cells
α_τ	transmittivity of modules
$\alpha\tau_e$	product of effective absorptivity and transmittivity
β_c	packing factor of solar cell in photovoltaic modules
β_o	temperature coefficient of electrical efficiency (%/K^{-1})
η	efficiency (percentage)
η_{mo}	efficiency at standard test condition (I(t) = 1000 W/m^2 and T_o = 25 °C) (percentage)
η_m	temperature dependent efficiency (percentage)
η_{th}	instantaneous thermal efficiency (percentage)
$\eta_{over,th}$	overall thermal efficiency (percentage)
$\eta_{over,\ ex}$	overall exergy efficiency (percentage)
ω	temperature dependent coefficient (%/K)

crystalline silicon (m-Si), poly crystalline silicon (p-Si) and in advanced thin technology, amorphous silicon thin film (a-Si), cadmium telluride (CdTe) and copper iridium gallium selenide (CIGS) are market available technologies. Among these m-Si still possess largest market share due to its high efficiency though slow energy intensive manufacturing process make it a expensive option [28–30]. Numerous approaches have been taken to reduce the cost of mono-crystalline photovoltaic cell, while the development of poly-crystalline photovoltaic cell has given a new dimension and substantial push towards crystalline based photovoltaic technologies. Among advanced thin film technology, a-Si has attained a significant market share due to low manufacturing cost and being cost effective for low temperatures application. CdTe and CIGS show potential in future aspects, still several research groups are consistently working with aim to increase efficacy and achieve low capital intensive manufacturing process [31–35]. From aesthetic point of view, both CdTe and CIGS are considered as more desirable options due its ductility and wall mounting susceptibility. Photovoltaic modules or panels usually contain six layers; covering glass, Anti-reflecting coating (ARC), solar cell or thin film, Ethylene Vinyl Acetate (EVA) layer, metal sheet as back cover and tedlar layer. The tempered glass is used as a covering glass that has gone through rapid heating and cooling to improve its quality, and has high transmittance. ARC is typically of nanometer thickness for providing feasible path to incident photons into solar cell. Some photovoltaic modules use wafer or film depending upon the technology used in manufacturing process. Ethylene Vinyl Acetate (EVA)/ Polyvinyl Butyral (PVB) is used in encapsulation of solar cell with a covering glass. In rear side of solar cell/thin film, metal contact (gold/silver/aluminium) is used by screen printing process. Some photovoltaic modules such as mono crystalline, polycrystalline silicon use polyvinyl fluoride as a tedlar for additional insulation whereas all other technologies based, and especially thin film use tempered black glass. Due to thick lamination, CIGS does not use back cover [13,30–35].

This reviewing summary suggested that a considerable amount of