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Energy modeling of photovoltaic thermal systems with corrugated unglazed transpired solar collectors – Part 1: Model development and validation

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Abstract

Building-integrated photovoltaic–thermal (BIPV/T) systems with unglazed transpired solar collectors (UTCs) can provide a key solution for on-site electricity and thermal energy generation. Although the energy saving potential of this technology is significant, no systematic thermal analysis model has been developed for optimal system design and integration with building operation. This paper is the first of two companion papers focused on modeling and performance analysis of BIPV/T systems with UTC. In Part 1, energy models are presented for two configurations: UTC only and UTC with PV panels, to predict the cavity exit air temperature and plate surface temperature with weather (incident solar radiation, ambient air temperature, dew point temperature and wind speed) and design (airflow rate or suction velocity and geometry) parameters used as inputs. Nusselt number and effectiveness correlations, representing both the exterior and interior convective heat transfer processes, have been obtained from experimentally validated, three-dimensional, Reynolds-Averaged Navier–Stokes (RANS), Computational Fluid Dynamics (CFD) simulations, using high resolution grids and the ReNormalization Group Methods k–ε (RNG k–ε) turbulence closure model. The energy models were validated with measurements in an outdoor test-facility. Good agreement was observed between the model prediction and the experimental data, with the root mean square error (RMSE) being within 1 °C for the UTC-only model and within 2 °C for the model of UTC with PV modules. In the companion paper, Part 2, the effects of important parameters on system performance are demonstrated based on information from the literature and simulations using CFD and energy models. The optimal geometry is investigated for both configurations and the performance curves, under different levels of solar radiation, wind speed and suction velocity, are presented to provide guidelines for system design.

Keywords: Energy modeling; Building-integrated photovoltaic–thermal systems; Transpired solar collectors; Corrugated surface

1. Introduction

Building energy demand in the United States has increased by 300% during the past 50 years and so it is not surprising that significant attention has been given to improving the energy performance of buildings. The net zero energy consumption concept for buildings is viewed as a means to reduce carbon emissions and dependence on fossil fuels, by harvesting energy on-site through environmentally-friendly technologies, such as solar, and utilizing highly efficient Heating, Ventilation and Air Conditioning (HVAC) systems to reduce the overall use of energy. One of these enabling technologies, building-integrated photovoltaic–thermal (BIPV/T) systems with unglazed transpired solar collectors (UTCs), can be a key solution to the energy and environmental challenges faced in building design. In UTC systems, dark porous metal

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Nomenclature

A_c	total collector area, m^2
A_{PV}	total PV panel area, m^2
C_p	specific heat capacity of air, J/kg K
d	gap between PV modules, m
D	cavity width, m
D_h	hydraulic diameter of the cavity, m
e	Corrugation amplitude, m
F_{bp}	view factor between the UTC plate and the back wall
G	incident solar radiation on the UTC plate per unit area, W/m^2
H	PV module height, m
$h_{c.b}$	convective heat transfer coefficient between the cavity air and the back wall
$h_{c.ext}$	convective heat transfer coefficient between the UTC plate (PV panel) and ambient air
$h_{c.int}$	convective heat transfer coefficient between the UTC plate (PV panel) and cavity air
i	control volume index
L	corrugation slope length, m
L_p	plate length, m
Nu_b	Nusselt number based on the hydraulic diameter and $h_{c.b}$
Nu_{ext}	Nusselt number based on L_p and $h_{c.ext}$
Nu_{int}	Nusselt number based on L_p and $h_{c.int}$
p	corrugation wavelength, m
P	PV module length, m
P_{PV}	electrical power generated by the PV panels, W/m^2
Q_{conv}	convective heat flux between difference surfaces (or air), W/m^2
Q_{gain}	thermal heat gain from the collector, W
Q_{rad}	radiative heat flux between different surfaces, W/m^2
Q_{solar}	solar radiation absorbed by the plate (or PV module), W/m^2
Re_b	Reynolds number based on the hydraulic diameter and the air velocity inside the cavity
Re_U	Reynolds number based on L_p and wind speed
Re_V	Reynolds number based on L_p and suction velocity
t	hour of the day
T_a	ambient air temperature, K
T_b	back wall temperature, K
T_c	Cavity exit air temperature, K
T_{dp}	dew point temperature, K
T_p	UTC plate surface temperature, K
T_{PV}	surface temperature of the PV panel, K
T_{ref}	PV surface temperature under standard test condition, K
T_s	air temperature through the perforation, K
T_{sky}	sky temperature, K
U_∞	external wind speed, m/s
V_s	mean suction velocity, m/s
w	corrugation crest length, m

Greek symbols

β_{ref}	temperature coefficient of the PV module, %/K
γ	$\gamma = Re_V^2/Re_U$
ε	effectiveness of the exterior convective heat transfer
ε_b	emissivity of the back wall
ε_p	emissivity of the UTC plate (PV panel)
η_{PV}	electrical efficiency of the PV panels, %
η_{Tref}	electrical efficiency of the PV panels under standard test condition, %
σ	Stefan–Boltzmann constant, 5.67×10^{-8} $W/(m^2 K^4)$

Abbreviation

BIPV/T	building-integrated photovoltaic–thermal
CFD	Computational Fluid Dynamics
CHTC	convective heat transfer coefficient
HVAC	Heating, Ventilation and Air-Conditioning
NOC	normal operating condition
PV	photovoltaic
PV/T	photovoltaic/thermal
RANS	Reynolds-Averaged Navier Stokes
RMSE	root mean square error
RNG	ReNormalization Group methods
STC	standard test condition
TI	turbulence intensity
TKE	turbulent kinetic energy
UTC	unglazed transpired solar collectors

sheets (flat or corrugated) are installed as the exterior layer of the building façade with a narrow gap beneath them. Corrugated UTCs have a more complex geometry, which makes them more difficult to analyze. However, this geometry can facilitate the integration of photovoltaic–thermal (PV/T) systems with PV panels partially covering the corrugated plate (Fig. 1). Ambient air is drawn through small perforations (with very low porosity of around 1–2%, evenly distributed on the UTC surface), taking away the absorbed heat while cooling down the PV panels. The collected heat can then be used to preheat ventilation air and/or to serve as the heat source for a solar-assisted heat pump, potentially coupled with a thermal storage tank, thus satisfying a significant part of the building's heating and/or hot water requirements while also generating electricity. The concept of distributed inlets, utilized in UTCs, where the air enters the cavity through small perforations over the entire collector area and is used to eliminate