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Development of a dynamic model for a hybrid photovoltaic thermal collector – Solar air heater with fins

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ABSTRACT

A dynamic model for a hybrid Photovoltaic Thermal Collector-Solar Air Heater (PVT-SAH) with longitudinal fins was developed to enable assessment of the potential of the system to provide high temperature outlet air (60–90 °C) under dynamic boundary conditions. The model description includes the method for discretising the system into a number of control volumes, the energy balance equations for each control volume and the implementation of the numerical solution. Model validation has been successfully undertaken by using empirical verification of model predictions with an experimental facility and by comparing the model outputs with the reference data from the literature. The dynamic PVT-SAH model was then used under variable boundary conditions and its performance was compared with an equivalent steady state model. Significant Time Constants (TC) were observed and it was found that the steady state model could overestimate the thermal energy gains of PVT-SAH by 35% when compared with the predictions of the dynamic model. Additional simulations were run under fixed boundary conditions to shown the effect of fins on the performance of the PVT-SAH system. Finally, to demonstrate the benefits of using such a dynamic PVT-SAH model, a case study was used and the effect of length ratio of PVT to SAH was investigated by using a range of performance criteria.

1. Introduction

Air based photovoltaic thermal (PVT) collectors utilise solar energy to generate both electricity and low grade thermal energy. The thermal energy collected from PVT collectors can be directly used for space heating or potentially used to drive desiccant wheels for space cooling of both residential and commercial buildings. However, a relatively high temperature energy source (60–90 °C) is often required in desiccant wheels for desiccant regeneration [1]. To achieve the target regeneration temperature, PVT systems can be connected in series. However, the local temperature of the PV absorber will increase with increasing PVT length. The excessive high temperature will bring challenges to the operation of PV panels, resulting in a decreased electrical efficiency, irreversible damages of the PV cells, and reduced lifespan of the PVT system. An alternative approach to achieving high outlet air temperature is to connect PVT systems with solar air heaters (SAH) in series. As the addition of fins has been considered as one of effective approaches to enhancing the thermal and electrical performance of PVT and SAH [2–9], the performance of the hybrid PVT-SAH system can be further enhanced by attaching longitude fins in the air channels to improve heat transfer between the absorber and the air flowing through the channels. A single layer of glass with a stagnant air layer between the glass cover and the PV absorber plate can also be used to increase the thermal resistance, and thereby further increase the temperature of the outlet air. A novel design of hybrid PVT-SAH system with fins is presented in Fig. 1. The PVT and SAH have the same width, and the SAH is connected to the outlet of PVT in order to further increase the air temperature. The longitude fins are attached between the absorber plate and bottom plate of both PVT and SAH and divide the air channel into a number of small passages.

Numerical modelling and simulations have been widely used to evaluate the performance and optimise the design of PVT and SAH systems. Tchinca [10] provided a comprehensive review of mathematical models for different types of SAH systems. A high number of numerical simulations have also been conducted to investigate the thermal and electrical performance of PVT collectors [11–18]. However, most mathematical models developed in the previous studies were steady state models where the heat storage capacity of PVT and SAH is not considered. The output parameters of steady state models

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Nomenclature

A	areas of each control volume along the length (m^2)
A_{cs}	cross-section areas of fins in contact with absorber and bottom plate per control volume along length (m^2)
A_{fin}	surface areas of fins for a control volume in contact with flowing air (m^2)
c	dimensionless ratio of A_{cs} to A
e	dimensionless ratio of A_{cs} to A_{fin}
C	Specific heat capacity ($kJ/kg \cdot K$)
D_h	hydraulic diameter of each air channel (m)
g	gravitational constant (m/s^2)
h_w	wind convection coefficient ($kJ/hr \cdot m^2 \cdot K$)
h_{nc}	natural convection coefficient for stagnant air layer ($kJ/hr \cdot m^2 \cdot K$)
h_c	forced convection coefficient ($kJ/hr \cdot m^2 \cdot K$)
h_r	radiation heat transfer coefficient ($kJ/hr \cdot m^2 \cdot K$)
h_{pv-p}	Conduction heat transfer coefficient between PV plate and absorber plate ($kJ/hr \cdot m^2 \cdot K$)
U_t	Top heat loss coefficient ($kJ/hr \cdot m^2 \cdot K$)
U_b	back heat loss coefficient ($kJ/hr \cdot m^2 \cdot K$)
R	thermal resistance ($hr \cdot m^2 \cdot K/ kJ$)
I_t	global incident solar radiation on PVT-SAH surface ($kJ/hr \cdot m^2$)
I_b	incident beam radiation on PVT-SAH surface ($kJ/hr \cdot m^2$)
I_d	sky diffuse radiation ($kJ/hr \cdot m^2$)
I_h	the horizon diffuse radiation ($kJ/hr \cdot m^2$)
K	Thermal conductivity ($kJ/hr \cdot m \cdot K$)
W	width of PVT-SAH (m)
L	Length (m)
$\dot{M}_f$	air mass flow rate (kg/hr)
M	mass per unit area (kg/m^2)
T	Temperature (K)
E	Primary energy saving
t	time (hr)
Δy	thickness (m)
Δt	time step for simulation (hr)
Δx	length of each control volume (m)
V_w	Wind speed (m/s)
H_{fin}	fin height (m)
d	distance between glass cover and absorber plate (m)

Greek symbols

α	absorptivity
$\varnothing$	inclination angle of integrated PVT-SAH (deg)
ε	emissivity
τ	transmissivity
$(\tau\alpha)$	product of transmission and absorption
μ	viscosity coefficient of air ($Pa \cdot s$)
ρ	density (kg/m^3)
η	instantaneous efficiency
σ	Stefan-Boltzmann constant, equals to 5.6703×10^{-8} $W/(m^2 \cdot K^4)$
γ	weighting factor of explicit equation in combined energy balance equations
ζ	PVT covering factor

Subscripts

i	the i_{th} control volume along the length of integrated PVT-SAH
g	glass cover
pv	PV plate
p	absorber plate
fin	longitudinal fins
f	flowing air
b	bottom plate
ad	adhesive layer
$insu$	Insulation materials
amb	ambient air
w	wind
th	thermal energy
ele	electricity gains
sky	sky
in	Inlet of a control volume
out	outlet of a control volume

Dimensionless terms

Re	Reynold number
Nu	Nusselts number
Pr	Prandtl number
Ra	Rayleigh number

at each time step are only a function of design parameters and boundary conditions of the same time step, and do not account for the thermal inertia from the previous time steps. However, the weather conditions are subject to quick and frequent fluctuations within a short period, and the effect of the time constant of the PVT or SAH systems could be significant. In such cases, steady state models might lead to an over- or under- prediction of the thermal output. Schnieders [19] reported that compared with a dynamic model for SAHs, a steady state model could lead to up to 15% of overestimation of daily yield of thermal energy when 1-min input data was used. Applications where dynamic modelling is essential for PVT or SAH include: the investigation of operational control strategies, performance comparison with experiments working under dynamic weather conditions and interactions with other system components which often require dynamic output data from PVT or SAH as input parameters. For example, if a solar collector is connected with an auxiliary heater, the accurate prediction of the outlet fluid temperature from the solar collector will significantly influence the economical operation of the auxiliary heater. Despite the advantages of dynamic models for SAH and PVT systems, only a limited number of such models have been developed in the past.

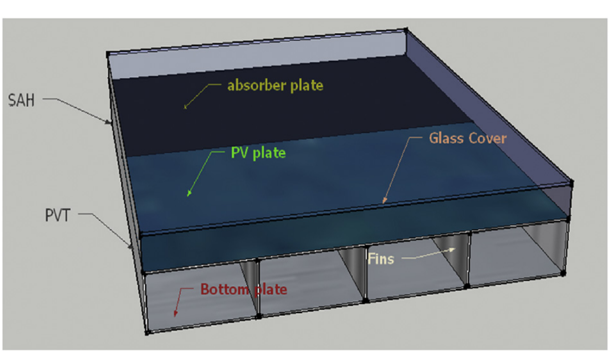

Fig. 1. Schematic of a hybrid PVT-SAH system.

This study presents the development of a dynamic model for a high-temperature PVT/SAH system with fins for potentially driving