Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 118 (2015) 175–185
SOLAR ENERGY
www.elsevier.com/locate/solener

Dimensionless and thermodynamic modelling of integrated photovoltaics–air source heat pump systems

Chenguang Wang [a], Guangcai Gong [a,*], Huan Su [a], Chuck Wah Yu [b]

[a] Civil Engineering College, Hunan University, Changsha 410082, China
[b] International Society of the Built Environment (ISBE), Milton Keynes, UK

Received 24 September 2014; received in revised form 16 February 2015; accepted 21 April 2015
Available online 9 June 2015

Communicated by: Associate Editor Claudio Alejandro Estrada-Gasca

Abstract

It is necessary to know the max photovoltaic power generation and the thermodynamic performance of the integrated system when the photovoltaic system is integrated with the air source heat pump (ASHP). A dimensionless method to model the max PV conversion efficiency of the monocrystalline silicon cell by the light intensity and environmental temperature has been introduced in this paper. To evaluate the validation of the engineering application of the dimensionless model, exergy efficiency and exergy consumption cost of the integrated PV driven ASHP system (PV-ASHP) have also been modelled based on the max PV conversion efficiency. The dimensionless model of a PV module was developed based on the ambient air temperature and light intensity in the laboratory. The max difference between the actual values and the prediction values is less than 0.28%. The dimensionless model can be used in the practical application in Central-south China with a modified factor of 0.75. The results of a case study in Changsha, China show that the relative error of the exergy efficiency model of the integrated PV-ASHP system is less than 4.21%. The relative error of the exergy consumption cost model of the integrated PV-ASHP system is 1.5% for cooling and 0.3% for heating. The results illustrate the accuracy and the validity of the dimensionless model and thermodynamic model for validating the PV-ASHP system. The dimensionless method provided in this paper also could be used to predict the different types of PV modules such as the polycrystalline silicon photovoltaic cell. The thermodynamic model of the integrated PV-ASHP system also could be used to investigate the efficacy of the integrated PV-ASHP.

Keywords: Air source heat pump; Dimensionless; Photovoltaic; Thermodynamic

1. Introduction

Integrated Photovoltaics (PV) systems for building applications are important consideration and effective solution to achieve zero or low-carbon objectives required by many governments and to reduce greenhouse gas emissions and ambient air pollution (Kylili and Fokaides, 2014; Mekhilef et al., 2012). It is necessary to know the output characteristics of PV modules when they are applied for building. Many workers have evaluated various standard output models of silicon solar cells by an evaluation of the current density and voltage in the solar cell (Bashahu and Habyarimana, 1995; EL-Adwi and AI-Nuaim, 2002; Haouari-Merbah and Belhamel, 2005; Kaminski and Marehand, 1997; Kiran and Inan, 1999; Ouennoughi and Chegaar, 1999). Different environmental parameters have also been introduced to modify the standard models, which can be used to predict the output features of the solar cell in various environmental conditions (King et al., 1998,

* Corresponding author. Tel.: +86 13973123865; fax: +86 731 88823082.
E-mail address: gcgong@hnu.edu.cn (G. Gong).

http://dx.doi.org/10.1016/j.solener.2015.04.036
0038-092X/

Nomenclature

I	PV output current (A)
I_L	PV photocurrent (A)
q	electronic charge (1.6×10^{-19} C)
I_0	diode reverse saturation current (A)
U	PV output voltage (V)
R_s	equivalent series resistance (Ω)
K_1	diode ideality factor ($1 \leqslant K_1 \leqslant 2$)
K	Boltzmann constant (1.38×10^{-23} J/K)
T_{PV}	temperature of PV module (K)
R_{sh}	equivalent parallel resistance (Ω)
η_1	Sun energy absorbed ratio of solar cell panel
S	light intensity (W/m^2)
h_f	heat transfer coefficient of the front panel (W/m^2 K)
h_b	heat transfer coefficient of the back panel (W/m^2 K)
T_f	temperature of the front panel (K)
T_b	temperature of the back panel (K)
ε_f	emission ratio of the front solar cell panel
ε_b	emission ratio of the back solar cell panel
σ	Stephen Pohl Seidman constant [5.67×10^{-8} W/(m^2 K^4)]
T_0	environment air temperature (K)
T_{sky}	sky temperature (K)
Q_{pe}	heat caused by the Joule effect in solar cell (W)
Q_s	heat caused by the temperature rising of the solar cell panel (W)
A	the area of the solar cell panel (m^2)
P_{out}	output power of the monocrystalline silicon solar cell (W)
β	modified factor of the temperature of the solar cell (0.03 K m^2/W for monocrystalline silicon solar cell)
$I_{0.ref}$	diode reverse saturation current at reference condition (A)
$E_{g,ref}$	band gap at reference condition (eV)
$R_{s,ref}$	equivalent series resistance at reference condition (Ω)
S_{ref}	light intensity at reference condition (W/m^2)
T_{ref}	environment air temperature at reference condition (K)
$R_{sh,ref}$	equivalent parallel resistance at reference condition (Ω)
η	output efficiency of solar cell
φ	PV efficiency factor (m^2/W K)
b_1	index for thermal environment parameters
b_2	index for thermal environment parameters
η_{max}	max transfer efficiency of solar cell
$Ex_{power,PV}$	output electricity exergy of solar cell (J)
$E_{power,PV}$	output electricity energy of solar cell (J)
$Ex_{output,ele-sys}$	output exergy of the electricity storage and inverter system (J)
$Ex_{input,ele-sys}$	input exergy of the electricity storage and inverter system (J)
η_{sto}	efficiency of D.C batteries
η_{inv}	inverter efficiency of the A.C inverter
W_{comp}	input power of compressor (J)
W_{fan}	input power of fan (J)
Ex_{en}	input environment exergy (J)
$Ex_{input,hp}$	input exergy of the heat pump system (J)
$Ex_{output,hp}$	output exergy of the heat pump system (J)
Ex_c	cold exergy (J)
Ex_h	heat exergy (J)
T_{en}	environment temperature (K)
T_c	average temperature of cold medium (K)
Q_c	cooling capacity (J)
Q_h	heating capacity (J)
T_h	average temperature of heat medium (K)
$Ex_{input,e}$	input exergy of the state grid (J)
η_{Ex}	total exergy efficiency of the integrated system
$Ex_{output,sys}$	output exergy of the integrated system (J)
$Ex_{input,sys}$	input exergy of the integrated system (J)
$Ex_{cons,PV}$	exergy consumption of PV system in construction process (J)
N	total life expectancy (Year)
H	annual working hours (Hour)
ϕ	practical modified factor of the PV system
$Ex_{cons,unit}$	exergy consumption per unit investment (J)
C_{PV}	unit exergy cost of photovoltaic system (Yuan/MJ)
C_{en}	unit cooling or heating exergy cost (Yuan/MJ)
C_e	unit exergy cost of state grid (Yuan/MJ)
C_1	annual initial cost of the integrated system (Yuan)
C_2	annual maintenance cost (Yuan)
$C_{initial}$	total initial investment of the integrated system (Yuan)
S_v	residual economic value after life cycle (10%)
i	the bank interest rate (3.5%)
$P_{des,PV}$	designed PV output power (kW)

2004; King and Sandia, 2000; Messenger and Ventre, 2004; Sehrode, 1998; Soto et al., 2006; Virtuani et al., 2003). All of these work focused mainly on the standard model of the solar cell based on the output current–voltage (I–U) characteristic of the solar cell. Few literatures reported the dimensionless model to describe the output characteristic of the solar silicon cell.

There have been researches to connect the PV module with a heat pump system. These focused mainly on recovery of the heat generated from the PV modules or PV/T