Solar Energy 170 (2018) 1118–1129

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A hybrid PV/T solar evaporator using CO_2: *Numerical heat transfer model and simulation results*

Pierre-Luc Paradis[a,*], Daniel R. Rousse[a], Louis Lamarche[b], Hakim Nesreddine[c]

[a] *Industrial Research Group in Energy Technologies and Energy Efficiency (t3e), École de technologie supérieure, Université du Québec, 1100, rue Notre-Dame Ouest, Montréal, Québec, H3C 1K3, Canada*
[b] *École de technologie supérieure, Université du Québec, 1100, rue Notre-Dame Ouest, Montréal, Québec, H3C 1K3, Canada*
[c] *Laboratoire des technologies de l'énergie (LTE), Hydro-Québec, 600 rue de la Montagne, Shawinigan, Québec, G9N 7N5, Canada*

A R T I C L E I N F O

Keywords:
Solar collector
PV/T
Two-phase flow
Transcritical heat pump
Carbon dioxide
Finite volume

A B S T R A C T

This paper investigates a new geometry of hybrid photovoltaic/thermal (PV/T) solar collector used as an evaporator in a CO_2 transcritical heat pump system. The solar absorber plate embeds monocrystalline silicon PV cells producing electricity and a stainless steel sheet to improve heat transfer with respect to standard back sheets. A serpentine stainless steel tube is bonded to the back of this solar absorber plate and two-phase CO_2 flows inside this heat exchanger.

A semi-transient numerical model is proposed to assess the thermal and electrical performances of the evaporator under given weather parameters and heat pump operating conditions. The 2-D, transient thermal diffusion equation is combined with a 1-D, steady state, compressible, two-phase flow model to compute the temperature distribution of the solar absorber plate along with the pressure, velocity, density and enthalpy field of the CO_2 in the serpentine tube. A special model based on the straight fin analytical model accounting for the circumferential temperature gradient around the tubes is developed to combine the absorber plate and the heat exchanger models.

The simulation results show an overall mean temperature reduction of the solar absorber plate operating at an electrical maximum power point of more than 25 °C with respect to a standard PV collector. Reducing the plate temperature leads to an additional production of 34 W of electrical power exceeding the maximum power specified under the test conditions of IEC 60904-3 international standard. In the simulated conditions, 1.028 kW of thermal power is also extracted and can be used in heating applications. The electrical efficiency increases from 14.1% for a standard solar PV collector to 16.0% for the suggested evaporator design. Finally, an overall efficiency combining both the electricity and heat production of 72.3% is achieved.

1. Introduction

1.1. Context

Hybrid PV/T solar collectors are commonly connected to air or water loops (Zondag, 2008). In those cases, they either produce hot water or preheat building fresh air. The use of a two-phase flow heat transfer fluid inside the solar collector in combination with a vapor compression cycle is another option known as direct expansion solar assisted heat pump (DX-SAHP) (Daghigh et al., 2010). It has a significant potential to improve performances of both systems at the same time (Chaturvedi et al., 1982). Accordingly, Ji et al. (2008a) designed a hybrid PV/T evaporator and tested it in a system using R22 as a refrigerant. It produced more energy (both electrical and thermal) per square meter than the separate components (either a standard PV solar collector or a thermal collector) could produce. In fact, the evaporation of the refrigerant inside the solar collector reduces the PV cells operating temperature and increase their electrical performances. At the same time, the increased evaporating temperature of the heat pump increases its heating coefficient of performance (COP).

An accurate model of this new design of hybrid PV/T solar evaporator is needed in order to predict its combined thermal and electrical performances and its influence on the thermodynamic cycle of the heat pump.

The existing analytical model based on the flat plate solar thermal collector original analysis conducted by Hottel and Whillier and available in reference textbook such as Duffie and Beckman (2006) relies on numerous assumptions. Modified versions of this model

* Corresponding author.
E-mail addresses: pierre-luc@t3e.info (P.-L. Paradis), daniel@t3e.info (D.R. Rousse), louis.lamarche@etsmtl.ca (L. Lamarche), nesreddine.hakim@ireq.ca (H. Nesreddine).

https://doi.org/10.1016/j.solener.2018.06.015
Received 10 March 2018; Received in revised form 14 May 2018; Accepted 4 June 2018
0038-092X/

Nomenclature

Symbols

L_x	collector width, [m]
dx	length of a differential control volume along the "x" axis, [m]
L_y	collector length, [m]
dy	length of a differential control volume along the "y" axis, [m]
L_z	serpentine tube heat exchanger length, [m]
dz_f	length of a differential control volume along the "z_f" axis, [m]
dz_P	length of a differential control volume along the "z_P" axis, [m]
q	heat transfer rate, [W]
c_p	specific heat capacity at constant pressure, [J/kg·K]
k	thermal conductivity, [W/m·K]
h	convection coefficient, [W/m^2·K] / enthalpy, [kJ/kg]
T	temperature, [K]
G	solar radiation, [W/m^2]
V_z	flow velocity, [m/s]
p	pressure, [kPa]
P	electrical power, [W]
I	electric current, [A]
V	electric voltage, [V]
x_{th}	thermodynamic vapor quality, [–]
$\hat{x}$	flow vapor quality, [–]
N_x	number of nodes along the "x" axis
N_y	number of nodes along the "y" axis
$N_{z,f}$	number of nodes along the "z_f" axis
$N_{z,P}$	number of nodes along the "z_P" axis
g_z	gravity constant, [m/s^2]
R	thermal resistance, [K/W]
R'	thermal resistance associated to heat transfer per unit length, [K·m/W]
w	width, [m]

Greek Symbols

δ	thickness, [m]
ρ	density, [kg/m^3]
ε	void fraction, [–]
μ	dynamic viscosity, [N·s/m^2]
θ	tilt angle of the pipe with reference to the horizontal, [rad]

Subscripts and superscript

a	related to the ambient air temperature
b	related to the bond between the plate and the serpentine tube
i	node identification along the spatial "x" axis
j	node identification along the spatial "y" axis
k	node identification along the spatial "z" axis
m	node identification along the time "t" axis
P	related to the solar absorber plate
f	related to the fluid mixture (both vapor and liquid phases)
friction	related to the pressure drop due to friction
elec	related to the photovoltaic electric production
cond	conduction heat transfer
conv	convection heat transfer
rad	radiation heat transfer
loss	related to the thermal loss to the ambient
st	stored energy
sky	related to the sky temperature
solar	related to the incident solar radiation
top	related to the heat transfer on the top of the plate
bot	related to the heat transfer on the bottom of the plate
fin	related to the straight fin model
CO_2	refrigerant or two-phase flow fluid
G	gas phase
L	liquid phase
T	total tilted solar radiation
in/out	inlet/outlet or inside/outside of the tube
wall	related to the heat transfer rate through the serpentine tube wall

Abbreviations

PV	photovoltaic
PV/T	photovoltaic/thermal
ODP	ozone depletion potential
GWP	global warming potential
CFC	chlorofluorocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
DX	direct expansion
DX-SAHP	direct expansion, solar assisted heat pump
COP	coefficient of performance
PDE	partial differential equation
MPPT	maximum power point tracking conditions

(Bergene and Løvvik, 1995; Florschuetz, 1979; Sandnes and Rekstad, 2002) take into account the photovoltaic power produced which reduces the thermal performances of the solar collector. These analytical models usually require small computation time. In this way, they can be used to evaluate both thermal and hybrid PV/T solar collector performances all year round. However, they cannot represent the complexity of the two-phase flow behavior, which characterizes a solar evaporator.

Distributed dynamic numerical models are also proposed (Chow, 2003; Pierrick et al., 2015; Rejeb et al., 2015). They help to understand the thermal and electrical behavior of the solar collector on the component scale since they include a high level of details. This kind of numerical model is then particularly well suited to analyze new collector geometries. In return, they are usually computationally intensive making them unsuitable to simulate the long-term system behavior.

1.2. Contribution of this work

This project involves a direct expansion (DX) hybrid PV/T solar collector, which acts as an evaporator of a transcritical CO_2 heat pump producing both electricity and heat. In an earlier contribution (Paradis et al., 2017), the combined thermal and electrical behavior of a solar absorber PV plate is analyzed in details. However, there was no heat exchanger to gather the thermal energy. The aim of the present paper is to include the coupling between the solar absorber PV plate model of Paradis et al. (2017) and a 1-D compressible two-phase flow model. In this new contribution, the previous model is first modified to take into account the source term due to the direct expansion heat exchanger and a complete 1-D compressible two-phase flow model is added to model the flow of CO_2. The purpose of the detailed numerical model is to