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Modeling and optimization of hybrid solar thermoelectric systems with thermosyphons

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Abstract

We present the modeling and optimization of a new hybrid solar thermoelectric (HSTE) system which uses a thermosyphon to passively transfer heat to a bottoming cycle for various applications. A parabolic trough mirror concentrates solar energy onto a selective surface coated thermoelectric to produce electrical power. Meanwhile, a thermosyphon adjacent to the back side of the thermoelectric maintains the temperature of the cold junction and carries the remaining thermal energy to a bottoming cycle. Bismuth telluride, lead telluride, and silicon germanium thermoelectrics were studied with copper–water, stainless steel–mercury, and nickel–liquid potassium thermosyphon-working fluid combinations. An energy-based model of the HSTE system with a thermal resistance network was developed to determine overall performance. In addition, the HSTE system efficiency was investigated for temperatures of 300–1200 K, solar concentrations of 1–100 suns, and different thermosyphon and thermoelectric materials with a geometry resembling an evacuated tube solar collector. Optimizations of the HSTE show ideal system efficiencies as high as 52.6% can be achieved at solar concentrations of 100 suns and bottoming cycle temperatures of 776 K. For solar concentrations less than 4 suns, systems with thermosyphon wall thermal conductivities as low as 1.2 W/mK have comparable efficiencies to that of high conductivity material thermosyphons, *i.e.* copper, which suggests that lower cost materials including glass can be used. This work provides guidelines for the design, as well as the optimization and selection of thermoelectric and thermosyphon components for future high performance HSTE systems.
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Keywords: Hybrid solar thermoelectric; Bottoming cycle; Solar thermal; Thermosyphon; STEG

1. Introduction

Efficient renewable energy sources are in significant demand to replace diminishing and environmentally harmful fossil fuels. The combination of commercial and residential buildings as well as the industrial sector currently consumes 72% of the total energy in the US (Davidson, 2005; Kelso, 2009). A significant portion of this energy is used in the form of heat, such as for hot water heaters in homes and food processing in industrial process heat (IPH) applications, where temperatures range from 50 °C to 1000 °C (Desideri et al., 2009; Demeter et al., 1991; Schnitzer et al., 2007; Lecuona et al., 2009). The abundance of solar energy promises efficient methods to meet the current heating and electricity needs. For example, hot water heaters have been commonly used in households (Han et al., 2010; Zhiqiang, 2005), and large scale solar thermal plants deliver distributed electrical power to cities (Manuel et al., 2002; Pacheco, 2001). In most cases, however, these systems are limited to providing either heat or electricity. More recently, hybrid systems with either photovoltaics or thermoelectrics to generate both electrical power and heat have been investigated. Hybrid photovoltaic-thermal

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Nomenclature

A	area (m^2)
C	solar concentration factor (–)
C_p	specific heat capacity (J/kg K)
C_s	pool boiling constant (–)
g	gravitational constant (N/kg)
G	incident radiative heat flux (W/m^2)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of vaporization (J/kg)
$h_{f,E}$	evaporator thin film evaporation heat transfer coefficient (W/m^2 K)
$h_{p,E}$	evaporator liquid metal pool boiling heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L_a	adiabatic section length (m)
L_c	condenser section length (m)
L_e	evaporator section length (m)
L_f	evaporator thin film length (m)
L_o	total thermosyphon length (m)
L_p	liquid metal pool height (m)
L_{te}	thermoelectric leg length (m)
M	molecular mass (kg/kmol)
$\dot{m}$	mass flux (kg/m^2 s)
P	pressure (Pa)
P_c	critical pressure (Pa)
P_l	liquid pressure (Pa)
P_r	reduced pressure (–)
P_{te}	thermoelectric power (W)
q	heat flux (W/m^2)
Q_{loss}	emissive loss (W)
Q_{out}	bottoming cycle heat transfer (W)
Q_{solar}	solar heat input (W)
r_i	thermosyphon inner radius (m)
r_o	thermoelectric inner radius, thermosyphon outer radius (m)
r_{te}	thermoelectric outer radius (m)
R_1	evaporator wall radial thermal resistance (K/W)
R_2	evaporator liquid pool thermal resistance (K/W)
R_3	evaporator thin film thermal resistance (K/W)
R_4	vapor core axial thermal resistance (K/W)
R_5	condenser film thermal resistance (K/W)
R_6	condenser wall radial thermal resistance (K/W)
R_7	condenser wall axial thermal resistance (K/W)
R_8	liquid metal thin film evaporation interfacial thermal resistance (K/W)
R_9	liquid metal condensation interfacial thermal resistance (K/W)
R_{te}	thermoelectric element radial thermal resistance (K/W)
R	gas constant (J/kg K)
$\overline{R}$	universal gas constant (J/kmol K)
s	pool boiling constant (–)
t	thermosyphon wall thickness (m)
T	temperature (K/°C)
T_c	condenser outer wall/bottoming cycle temperature (K)
$T_{s,E}$	thermosyphon evaporator outer wall temperature, thermoelectric cold side temperature (K)
$T_{sat,E}$	thermosyphon evaporator saturation temperature (K)
$T_{sat,C}$	thermosyphon condenser saturation temperature (K)
T_{ss}	selective surface/thermoelectric hot side temperature (K)
$T_{vl,E}$	thermosyphon evaporator liquid vapor interface temperature (K)
$T_{vl,C}$	thermosyphon condenser liquid vapor interface temperature (K)
$T_{w,E}$	thermosyphon evaporator inner wall temperature (K)
$T_{w,C}$	thermosyphon condenser inner wall temperature (K)
T_∞	environment temperature (K)
x,y	coordinates (m)

Greek symbols

α	absorbtivity (–)
ε	emissivity (–)
η	efficiency (–)
η^*	efficiency as $k_w \to \infty$ (–)
ρ_R	reflectivity (–)
ρ	density (kg/m^3)
σ_B	Stefan–Boltzmann constant (W/m K^4)
σ	surface tension (N/m)
σ'	condensation coefficient (–)
τ	transmissivity (–)
μ	dynamic viscosity (Pa s)
δ	liquid film thickness (m)
θ	thermosyphon inclination angle from the vertical (°)

Superscript

DC	direct current
HSTE	hybrid solar thermoelectric system
IPH	industrial process heat
PV	photovoltaic
PVT	hybrid photovoltaic thermal
SS	selective surface
TE	thermoelectric
ZT	thermoelectric figure of merit
$\bar{}$	mean or average value

Subscripts

a	adiabatic
bb	black body
c, C	condenser
e, E	evaporator

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