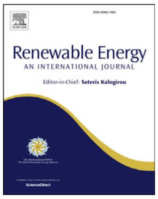
Renewable Energy 115 (2018) 299–307

Contents lists available at ScienceDirect

Renewable Energy

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



A novel hybrid cavity solar thermal collector

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ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form
10 July 2017
Accepted 18 August 2017
Available online 25 August 2017

Keywords:
Hybrid
Thermoelectric generation
Solar thermal collector
Solar energy

ABSTRACT

The present paper proposes a new hybrid system of solar thermal collector with a cavity receiver and thermoelectric generator (TEG). The heat rejected by the thermoelectric generator is utilized to heat the water in the collector. This system consists of two concentric cylinders, thermoelectric generator, two mirrors and heat exchanger. The main concept of this system is to provide electric power and self-storage of hot water without the need for any connecting pipe or storage tank of useful hot water. A prototype is constructed and a steady-state mathematical model of the collector is presented in details to describe the system thermal behavior and has been simulated using Microsoft office and goal seek tool to find the temperature of the thermoelectric generator. The results of the present system are illustrated in figures and tables that show the effect of (wind speed, mass flow rate on fluid, solar intensity radiation and thermo electric generator type) on the system performance.

1. Introduction

In the last few decades, many researchers all over the world are working on incremental developments that utilize clean and more sustainable energy resources to satisfy the demand of the world's growing and to overcome the serious environmental and atmospheric problems that have been resulted by human activities. Consequently, greenhouse emission, ozone layer depletion, global warming and climate change have started to pose a threat to our environment [1]. The impact of the above disasters can be abated by converting waste heat into electricity through thermoelectric generators (TEGs) that utilize the Seebeck effect by inducing electricity from any temperature gradient along its junction during the movement of charge carriers [2]. Thermoelectric generators are considered as a competitive solution for waste energy recovery, cooling applications and heat pumping [3], [4]. Many advantages are offered by thermoelectric generators compared to conventional electrical power generators systems such as having a longer lifetime because the lack of moving parts, compactness, being highly reliable and environmentally friendly [4] [5], [6]. However, the efficiency of thermoelectric generators is not exceeding 10% [2], therefore the optimization of thermoelectric devices efficiency is one of the essential research trends for solar power utilizations because their conversion efficiency is low compared to other devices and technologies [7]. Mainly, the major concern of this development is the limitations of the materials that are currently used for thermoelectric devices manufacture, and hence researchers are still working on developing thermoelectric materials by minimizing the thermal conductivity and maximizing the electrical conductivity and Seebeck coefficient to reach an effective heat transfer at the cold and hot plates and hence maintain the temperature gradient between the hot and cold side of the TEGs [8], [9]. Moreover, the effectiveness of thermoelectric is described by the dimensionless figure of merit, ZT, which is a dimensionless unit that depends on the Seebeck coefficient (α), absolute temperature (T), electrical conductivity (σ), and thermal conductivity (κ). The value of ZT is given by the following relation:

$$ZT = \frac{\alpha^2 \sigma T}{\kappa} \tag{1}$$

The fundamental principle of thermoelectric generators based on charge carriers: electrons (N-type) and holes (P- type) materials that have the capability to move freely through semiconductors and metals. Generally, thermoelectric generators technology is based on two principles, namely: Seebeck and Peltier effects. The

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http://dx.doi.org/10.1016/j.renene.2017.08.048
0960-1481/

Nomenclature

Symbol	
A_c	collector area (m^2)
A_g	surface area of glass layer (1) (m^2)
A_{ins}	the surface area of insulation layer (m^2)
A_N	cross-sectional area of the negative doped leg of each Thermoelectric unit. (m^2)
$A_{\boldsymbol{p},c}$	area of the cold side of TEMs (m^2)
A_P	cross-sectional area of the positive doped leg of each Thermoelectric unit. (m^2)
C_p	specific heat of water at constant pressure (kJ/kg.°C)
D	the outer diameter of the insulation layer (m)
F_R	the heat removal factor (−)
G	solar radiation intensity (w/m^2)
g	gravitational acceleration (m/s^2)
$h_{c,g}$	convection heat transfer coefficient along glass layer (1) (W/m^2.°C)
$h_{c,out}$	convection heat transfer coefficient to the ambient air (W/m^2.°C)
$h_{r,g}$	radiation heat transfer coefficient (W/m^2.°C)
I	amount of current produced by the TEMs (A)
k	thermal conductivity of water (W/m.°C)
k_a	thermal conductivity of the air (W/m.°C)
k_{eff}	effective thermal conductivity of water (W/m.°C)
k_{ins}	thermal conductivity of insulation material (W/m.°C)
k_N	thermal conductivity of the negative leg of the thermoelectric junction (W/m.°C)
k_P	thermal conductivity of the positive leg of the thermoelectric junction (W/m.°C)
L	length of the collector (m)
L_c	length scale in Ra_c (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number (−)
P	amount of electric power produced by the TMEs (W)
Pr	Prandtl number (−)
Q_C	amount of heat rejected from the TEMs (W)
$Q_{c,g}$	amount of convection heat loss from the glass layer (1) to the ambient air (W)
$Q_{c,in}$	internal free convection heat loss (W)
$Q_{c,o}$	convection heat loss to the ambient air (W)
Q_H	amount of heat transferred to the TMEs (W)
$Q_{i,in}$	internal insulation conduction heat loss (W)
Q_l	total amount of heat losses from the hot water (W)
$Q_{l,top}$	amount of heat losses from the glass layer (1) to the sky and to the ambient (W)
$Q_{r,g}$	amount of radiation heat loss to the sky (W)
Q_S	amount of heat input the system (W)
Q_{useful}	amount of useful heat produced from the system (W)
Ra_c	Rayleigh number (−)
$R_{c,in}$	the internal free convection resistance (W/K)
$R_{c,ins}$	the insulation conduction resistance (W/K)
$R_{c,o}$	the external convection resistance (W/K)
Re_D	Reynolds number (−)
R_{eff}	total electrical resistance of the thermoelectric modules (Ω)
R_L	the external load resistance (Ω)
R_{total}	the total heat resistance (W/K)
$r_{i,c}$	the inner cylinder radius (m)
$r_{o,c}$	the outer cylinder radius (m)
r_i	actual inner radius exposed to internal free convection (m)
r_o	actual outer radius exposed to internal free convection (m)
S_{NP}	Seebeck coefficient of two junctions (V/K)
T_1	hot junction temperature of TEMs (K)
T_2	cold junction temperature of TEMs (K)
T_3	temperature of outer cylinder (K)
T_4	temperature of insulation layer (K)
$T_{f,in}$	inlet fluid temperature (K)
T_g	glass layer (1) temperature (K)
T_{sky}	sky temperature (K)
T_∞	ambient air temperature (K)
U_l	overall heat transfer coefficient
V	wind speed (m/s)
α_w	thermal diffusivity (m^2/s)
α	absorptivity of TEMs (−)
β	volumetric thermal expansion coefficient (K^{-1})
$\in_g$	emissivity of glass layer (1) (−)
θ	angle of glass layers (Degree)
σ	Stephen-Boltzmann constant ($W/m^2.K^4$)
τ	transmissivity of the glass layer (−)
η_{system}	overall efficiency of the system (%)
η_{TEMs}	the efficiency of the thermoelectric modules (%)
ρ_N	electrical conductivity of the negative leg of the thermoelectric junction (Ω.m)
ρ_P	electrical conductivity of the positive leg of the thermoelectric junction (Ω.m)
ν	kinematic viscosity (m^2/s)

Seebeck effect describes a phenomenon in which a voltage difference is resulted between two electrical conductors or semiconductors that have different temperatures. On the other hand, the Peltier effect is based on the cooling of one junction and the heating of the other when electric current is maintained in a circuit of material consisting of two dissimilar conductors. Furthermore an alternative P-N type semiconductors are connected thermally in parallel and electrically in series with the typical thermoelectric generators, this give the capability for the electrons and holes to flow in opposite directions and hence forming an electric current and generating power [10].

Because of these advantages of thermoelectric generators, comprehensive attention has been placed on the improvements of TEGs in power generation technology in a various applications such as biomedical, industrial plants, computers, automobile engines, geothermal areas [6], aerospace [11] [12], military and remote power applications [13], [14]. On the other hand, it was shown that additional improvements on thermoelectric devices as heaters, power generators, or coolers are possible [2]. Since then, improvements may include the three physical properties: thermal conductivity, Seebeck effect and electrical resistivity [15]. In addition to this, researchers are still working on improving materials with figure-of −merit higher than 2.0 [16] by moving their orientations towards the using of nanostructure materials. Zhao et al. studied the thermoelectric and mechanical properties when adding nano-SIC into Bi_2Te_3 matrix and they have concluded that by adding nano-SIC the thermal conductivity was reduced, the Seebeck coefficient was increased and the electrical conductivity