Energy Conversion and Management 174 (2018) 417–429

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermal analysis and optimization of a system for water harvesting from humid air using thermoelectric coolers

M. Eslami[a,*], F. Tajeddini[b], N. Etaati[a]

[a] School of Mechanical Engineering, Shiraz University, Shiraz, Iran
[b] School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Thermoelectric cooler
Atmospheric water generation
Thermodynamic optimization

ABSTRACT

Condensation of water vapor available in atmospheric air can be considered as a solution for water scarcity problem. In this paper, a comprehensive thermodynamic analysis of water production from humid air using thermoelectric coolers (TECs) is presented. The system consists of a number of thermoelectric coolers, a fan to supply the required air flow circulation, two cold and hot air channels, heat sinks and solar cells for powering the thermoelectric coolers and fan. Effects of various design parameters are investigated and discussed. The proposed design is optimized to get the maximum effectiveness which is defined as the amount of produced water per unit of energy consumption. Sensitivity analysis is used to find the optimum number of TECs, length of the channels and performance of the system at different temperatures. The resulting system is capable of producing 26 ml of water within 1 h from the air with 75% relative humidity and the temperature of 318 K by consuming only 20 W of electrical power. In addition, the annual performance and optimization of this device in three southern cities of Iran are presented based on hourly meteorological data. Finally, comparison of the present system with other air water generators indicates that the proposed design is the most energy efficient system among similar devices especially in high relative humidity.

1. Introduction

Nowadays, water scarcity is one of the most serious issues in the world. Approximately, around 97.5% of the water content of the earth is salty seawater which means only 2.5% of the existing water is fresh. Almost 70% of this amount is frozen at the polar ice caps, and around 30% exists in the form of moisture in the air or underground aquifers. Therefore, it can be concluded that only less than 1% of the earth's fresh water is accessible for direct human use [1]. Mekonnen et al. [2] notified that as many as four billion people all around the world face the problem of water scarcity for at least one month per year. All these factors have brought about the need to study solutions addressing the water scarcity problem.

Among different methods of desalination, atmospheric water generation (AWG) can be an easy method for fresh water production especially for places with high relative humidity. In this approach, ambient air is cooled down below the dew point temperature and the condensed water is collected. Vapor compression refrigeration, absorption refrigeration and thermoelectric cooling (TEC) can be used for this purpose. Thermoelectric coolers are devices which function on the basis of Peltier effect. By passing an electric current through them, they produce a temperature difference resulting in a cooling effect. In comparison with vapor compression and absorption refrigeration, TEC devices have no moving parts and require less maintenance. Therefore, they are suitable for designing simple and portable AWG systems. However, the designer must be very careful about the performance and efficiency of TECs at various operating conditions.

There are different approaches to study properties and modeling the behavior of thermoelectric coolers [3–7]. Zhao and Tan [3] presented a study of material, modeling, and application of thermoelectric coolers. Fraisse et al. [4] compared different methods of modeling TECs. Also, Mani [5] studied the behavior of thermoelectric coolers numerically and analytically and revealed that the results of these two approaches are in good agreement.

The coefficient of performance is among the most important topics related to thermoelectric coolers. For this purpose, Enescu and Virjoghe [6] provided a review of thermoelectric cooling parameters and performance. In addition, Xuan [7] investigated the effect of thermal and contact resistance of thermoelectric coolers. Based on his studies, the amount of COP depends on thermoelectric length. Also by increasing the thermal contact resistance, this dependence increases significantly.

The maximum COP of a TEC device in both cooling and heating

* Corresponding author.
E-mail address: meslami@shirazu.ac.ir (M. Eslami).

https://doi.org/10.1016/j.enconman.2018.08.045
Received 25 April 2018; Received in revised form 2 August 2018; Accepted 12 August 2018

Nomenclatures

A_c	cross section area of a fin (m^2)
A_f	fins area (m^2)
A_t	total area (m^2)
C_p	specific heat (kJ/kg K)
COP	coefficient of performance
D	diameter (m)
Eff	effectiveness (L/J)
f	fraction factor
h	enthalpy (J/kg)
h_{conv}	convection heat transfer coefficient (W/m^2 K)
H	height of each channel's hole (m)
I	current (A)
k_f	thermal conductivity of base air flow (W/m K)
k_s	thermal conductivity of base plate material (W/m K)
K_m	TEC module thermal conductance (W/K)
l	length (m)
l_c	characteristic length (m)
N	number
Nu	Nusselt number
p	perimeter (m)
P	power (W)
Pr	Prandtl number
Q	transferred heat (W)
R	resistance (K/W)
R''	thermal resistance (m^2 K/W)
R_m	TEC module electrical resistance (ohm)
Re	Reynolds number
S_m	TEC module Seebeck coefficient (V/K)
T	thickness (m)
T	temperature (K)
u	air velocity (m/s)
V	voltage (V)
$\dot{V}$	volume flow rate of water (L/s)
w	width (m)

Greek symbols

η_0	overall surface efficiency
η_f	efficiency of fin with an adiabatic tip
ν	kinematic viscosity (m^2/s)
ΔP	pressure drop (Pa)
ΔT	temperature difference (K)
ρ	density (kg/m^3)
ϕ	relative humidity
ω	humidity ratio

Subscripts

a	ambient
c	cold side
equ	equivalent resistance
h	hot side
hyd	hydraulic
LMTD	log mean temperature difference
max	maximum
opt	optimum
t, b	resistance of the un-finned part of the heat sink
t, base	thermal resistance of the base surface
t, c	contact resistance
	resistance of the extended surfaces
TEC, m	thermoelectric cooler
w	water

mode is one of the important issues that should be considered. Cosnier et al. [8] examined the performance of thermoelectric coolers by experimental and numerical analysis and revealed that it is possible to reach the coefficient of performances above 1.5 for cooling mode, and 2 for heating mode. Also, Liu et al. [9] used thermoelectric coolers for various air conditioning applications and showed that it is possible to reach the COP of 2.59 for cooling mode and 3.01 for heating mode. These results suggest that TEC devices can be a good choice for water harvesting if they are used efficiently.

Reducing the hot side temperature of a thermoelectric cooler is an approach to increase the coefficient of performance. For example, Sadighi Dizaji et al. [10] used water flow for cooling the hot side of a TEC instead of air and showed that it is possible to increase the cold side performance of TEC significantly. Seo et al. [11] studied the effect of different heat sink's shapes on the performance of TECs, numerically and showed the shape of heat sinks can change the operating performance of thermoelectric coolers. Also Via'n and Astrain [12] designed a heat sink for the cold side of a TEC and showed that by using this heat sink, COP can increase up to 32%. In addition, Zhu et al. [13] studied the effect of different heat exchanger sizes on the performance of TECs theoretically. According to their studies, the highest amount of COP is achieved by using the optimal heat sink size.

Another important parameter that significantly affects the performance of a TEC is the electrical current. Tan et al. [14] applied the second law of thermodynamics and showed that the amount of current must be precisely determined to achieve the optimal cold side temperature. Also Tan and Fok [15] presented an approach to analyze and optimize a thermoelectric cooling system.

The application of TECs in water harvesting from air is reported in several experimental studies [16–24]. Vian et al. [16] designed a device which was able to condense 0.969 L of water from the air in each day. Furthermore, Jradi et al. [17] theoretically and experimentally studied a system including 5 channels with 20 thermoelectric coolers in each powered by solar cells. This device is combined with a solar distiller humidifying ambient air to increase distillate output of water production. They showed that it is possible to produce 10 L of water during a summer day in Beirut. In another study, Yao et al. [18] produced 33.1 g/h of water by using a dehumidification device having more heat sinks on the two sides of thermoelectric coolers. In addition, Atta [19] designed a prototype including three TEC elements and a photovoltaic cell. He applied this system in Yanbu climate conditions and could produce almost 1 Liter of condensed water per hour. Besides, Joshi et al. [20] installed 10 TEC in a channel with the length of 70 cm and tested it in several different climate conditions. Based on this design, they harvested 240 ml of water in 10 h at a relative humidity of 90% and mass flow rate of 25 g/s. Tan and Fok [21] designed an AWG system and investigated the effect of input power to TECs and inlet mass flow rate on the amount of produced water. They revealed that it is possible to produce 50 ml of water in 3 h in an average relative humidity of 77%. Also, Liu et al. [22] built a portable water generator with two thermoelectric coolers and investigated the effect of inlet air relative humidity and air flow rates and showed that the maximum amount of generated water is 25.1 g per hour with 58.2 W input power. Munoz-Garcia et al. [23] designed a similar system for irrigation of young trees. Based on this design, they could harvest 35 ml water per hour from the air. Moreover, Pontious et al. [24] could harvest 0.21 L of water in a day with 0.33 kWh of energy consumption.

Recently, Shourideh et al. [25] performed a theoretical and experimental analysis of a Peltier AWG by optimizing the cold side extended surface and the cooling system. But they didn't investigate the