Energy and Buildings 113 (2016) 51–60

Contents lists available at ScienceDirect

Energy and Buildings

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

Experimental and numerical investigation of a prototype thermoelectric heating and cooling unit

M. Zeki Yilmazoglu*

Gazi University Faculty of Engineering Department of Mechanical Engineering, Maltepe, Ankara, Turkey

ARTICLE INFO

Article history:
Received 16 July 2015
Accepted 24 December 2015
Available online 29 December 2015

Keywords:
Thermoelectric cooling
HVAC
Solar cooling
Psychrometry
Energy efficiency

ABSTRACT

In this study, the performance of a prototype thermoelectric heating/cooling unit is investigated. In the numerical analysis, temperature–pressure contours, and velocity vectors are obtained for the selected fin geometry. In order to validate the numerical results, experimental analyses are carried out. The effects of the air velocity on the temperature distribution of the fin surfaces and the variation of the psychrometric properties of the air are measured for various TEC voltage differences. Thermal images are used to obtain the temperature variation on fin surfaces. COP values for heating and cooling are calculated. For different fan speeds, the heating and cooling COP values vary between 2.5 and 5, and 0.4 and 1, respectively. The study shows that it is possible to use TECs as an alternative method for HVAC applications with properly designed heat exchangers. Integrating them with photovoltaic panels provides utilization of solar energy, especially in cooling applications.

1. Introduction

In recent years, in parallel with the developments in semiconductor materials, thermoelectric modules (TEM) have been used in many fields. In general, a thermoelectric module can be used for electricity generation or heat pump applications. Electricity generation is achieved under a specific temperature difference on both sides of the module by the Seebeck effect and it is called thermoelectric generator (TEG). Heating and cooling can be obtained by applying a voltage difference to the module depending on the Peltier effect, which is called thermoelectric cooler (TEC). Thermoelectric modules have been used in a variety of applications such as small volume refrigerators, portable coolers, solid-state lasers, infrared sensors, electronic cooling systems, aerospace applications, vehicle air conditioning systems, cryogenic surgery equipment, photovoltaic systems, and building active façade systems. TECs can be driven by photovoltaic modules to reduce the primary energy consumption of HVAC-R applications. The amount of the energy used in buildings for heating and cooling is approximately 40% of the total energy consumption which is indicated by US DoE Buildings Energy Data book. Therefore, an alternative energy efficient method is the main motivation of the researchers in this area. Energy consumption of an air conditioning system can be decreased with alternative methods that result in a reduction in the primary energy consumption.

Photovoltaic driven TECs are of great importance in terms of alternative cooling methods [1–5]. Wahab et al. [3] designed and tested a solar thermoelectric refrigerator. According to the results, the inside temperature of the refrigerator was decreased from 27 °C to 5 °C in 44 min with a COP of 0.16. Dai [5] also found that the COP value of a photovoltaic driven TEC was approximately 0.3. Min and Rowe [6] showed that, for 5 °C refrigerator inside temperature and 25 °C environment temperature, the COP value of the thermoelectric refrigerator was between 0.3 and 0.5. Khattab and El Shenawy [7] investigated to drive TECs by TEGs. It was shown that five TEGs were able to drive one TEC for Egypt climatic conditions.

A theoretical model for the optimization of TECs was developed by Zhou and Yu [8]. Zhang [9] suggested a general approach for the performance evaluation of TECs. According to the results, 9 A current was found to be critical for the optimum working conditions. Transient analysis of a TEC is of importance due to the thermal behavior of a system design. Numerical and analytical models were developed to predict the performance of the TEC under transient conditions [10–12]. In addition, steady state numerical models were developed [13–16]. According to the results, increasing the element number increases the cooling power of a TEC. Xuan [17] investigated the effects of ceramic plates on thermal and contact resistances. Moreover, it is worthful that the variation of the Seebeck coefficient with respect to the operating temperature directly affects the performance of the system. Karabetoglu et al. [18] investigated the Seebeck coefficient and electrical conductivity of Bi_2Te_3

* Tel.: +90 312 582 34 43; +90 532 701 41 59.
E-mail addresses: zekiyilmazoglu@gazi.edu.tr, zekiyilmazoglu@gmail.com

http://dx.doi.org/10.1016/j.enbuild.2015.12.046
0378-7788/

Nomenclature

COP	Coefficient of performance
h	Enthalpy, kJ kg^{-1}
I	Current, A
k	Thermal conductivity, W m^{-1} K^{-1}
$\dot{m}$	Mass flow rate, kg s^{-1}
P	Electric power, W
R	Electrical resistance, ohm
T	Temperature, K or °C
U	Velocity, m s^{-1}
V	voltage, V
$\dot{Q}$	Heat rate, W
Z	Figure of merit, K^{-1}

Greek Symbols

α	Seebeck coefficient, V K^{-1}
π	Peltier coefficient, V
σ	Electrical conductivity, Ω^{-1} m^{-1}
Φ	Relative humidity, %

Subscripts

c	Cold side or cooling
db	Dry-bulb
h	Hot side or heating
i	Inlet
o	Outlet
s	Surface
wb	Wet-bulb
pc	Peltier cooling
ph	Peltier heating
j	Joule heat
con	Fourier heat

with respect to temperature at 100–375 K range. The Thomson effect was investigated by Abdul-Du and Wen [19] and Lee [20]. Lee showed that the positive Thomson coefficient increases the performance of a TEC and vice versa. Tan and Fok [21] made a comparison study for the performance of the products of different thermoelectric module manufacturers. Heat exchanger designs to remove the heat on the surfaces of TECs have a critical importance on the performance of TECs. Zhu et al. [22] theoretically performed an optimum heat exchanger analysis for a TEC. Geometric optimization of a TEC was investigated by Huang et al. [23] with the conjugate gradient method. Wang et al. [24] developed a theoretical model for optimum configuration of TECs according to the entropy generation analysis. Merbati et al. [25] investigated the effects of pin geometry on a TEC performance, and thermal stress effects were also taken into consideration in the study.

The temperature of the cold side and the cooling capacity of a TEC can be decreased by multistage TECs. An analytical method was developed for two-stage TECs for predicting the performance of the module [26]. The performance of a refrigerator with multistage TECs was investigated by Pan et al. [27]. The performance comparison of single-stage and multistage TECs was investigated [28]. A three-dimensional model was developed for the performance optimization of two-stage TECs [29]. Putra et al. [30] investigated the performance of 5- and 6-stage TECs for cryogenic applications.

TECs have been used frequently in different application areas in buildings. Active building envelopes [31], green building applications [32], radiant cooling panels consisted by TECs [33], and air to air thermoelectric heat pumps [34] are some of the application areas of TECs for buildings. In addition, thermoelectric coolers have been widely used in electronics cooling in recent years [35–37]. It is also possible to use TECs as a temperature control device [38,39]. Jugsujinda [40] investigated COP values of a TEC and a TEC-integrated refrigerator. Miranda et al. [41] performed dynamic simulations of TECs, driven by dye-sensitized photovoltaic panels and tested the suggested system in vehicles. Air conditioning with TECs offers an alternative method for HVAC engineers. Riffat and Qui [42] compared TECs with vapor compression and absorption chillers. According to the results, absorption cooling systems were found to be more economical when the first investment cost and 11-year operating costs were included. Li et al. [43] investigated a TEC-integrated air conditioning system, and the COP value of the system was found to be 2.5. Yang et al. [44] reviewed the use of TECs in air conditioning and refrigeration applications. Han et al. [45] investigated the COP values of a thermoelectric ventilator for winter and summer conditions.

In this study, the performance of a prototype thermoelectric heating/cooling system was investigated. For this purpose, two antisymmetric ducts with fin and fan holes were manufactured. A TEC was placed between the fin holes. Fins were installed on hot and cold surfaces of the TEC. Numerical and experimental analyses were carried out to investigate the simultaneous heating and cooling performance of the system. In the numerical analysis temperature distribution, velocity vectors, and pressure drop were simulated. In the experimental part of the study, the effects of air velocity on the temperature distribution of the fin surfaces and the variation of the psychrometric properties of the air were investigated for various TEC voltage differences. The COP values of heating and cooling were calculated.

2. Thermoelectric modules

A thermoelectric module is achieved by connecting thermoelectric elements electrically in series and thermally in parallel. Thermoelectric elements consist of n and p type semiconductor materials. TECs work as heat pumps when a DC voltage is applied. Cold sides of TECs absorb heat from media and remove the absorbed heat to the environment. This cooling effect occurs by electron transfer between dissimilar semiconductor materials. Seebeck effect can be defined as producing a voltage difference in case of a temperature difference between two dissimilar electrical conductors or semiconductors. This voltage can be shown as indicated in Eq. (1). In this equation, α_{AB} is the relative Seebeck coefficient measured in VK^{-1}.

$$V = \alpha_{AB}\Delta T \tag{1}$$

The Peltier effect can be defined as the occurrence of a temperature difference at the ends of two dissimilar materials with the electric current passing. Current flowing through the circuit forces electrons to move from one junction to the other. The movement of the electrons causes one junction to lose heat, which is the cold side, and the other to absorb heat, which is the hot side. The Peltier effect can be stated as shown in Eq. (2), where π_{AB} and I are the Peltier coefficient and the current, respectively.

$$\dot{Q} = \pi_{AB} I \tag{2}$$

Peltier and Seebeck coefficients are in a relationship as indicated in Eq. (3). In this equation, T shows the absolute temperature in Kelvin.

$$\pi = \alpha T \tag{3}$$

According to the Peltier effect, cold end can absorb the heat and disseminate it to the other media via hot end. The use of TECs in heating and cooling applications has gained a momentum with the development of semiconductor materials. When using materials other than semiconductors, Joule heat causes the Peltier effect to be