International Journal of Heat and Mass Transfer 86 (2015) 843–852

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Energy and exergy analysis of thermoelectric heat pump system

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ARTICLE INFO

Article history:
Received 16 December 2014
Received in revised form 16 February 2015
Accepted 19 March 2015
Available online 8 April 2015

Keywords:
Exergy analysis
Thermoelectric heat pump
Irreversibilities
Exergy efficiency

ABSTRACT

Exergy analysis has gained significance in analysing thermal energy systems as it locates and quantifies the irreversibilities in the system. This paper investigates the thermoelectric heat pump systems through exergy analysis. Four thermodynamic models of the thermoelectric heat pump considering the internal and external irreversibilities are developed and analysed in MATLAB Simulink environment with temperature dependent material properties for various operating temperatures. Moreover, analytical expressions for exergy efficiency and irreversibilities for the thermoelectric heat pump are derived. The results show that the exergy efficiency of the thermoelectric heat pump increases with increase in ΔTh. For a typical operating condition in an irreversible thermoelectric heat pump with 31 thermocouples and when T_H and T_C of 313 K and 303 K respectively, the maximum energy and exergy efficiency obtained are 4.01 and 12.81% at same optimum current of 5.55A. The results also show that the effect of internal irreversibilities is more pronounced than the external irreversibilities in the performance of the thermoelectric heat pump. The effects of irreversible heat transfer and contact resistance in the exergy efficiency are also studied. This study will be helpful in designing the actual thermoelectric heat pump systems.

1. Introduction

Thermoelectric devices are solid state direct energy conversion devices for converting heat into electricity and vice versa [1–4]. It operates on the combination of Seebeck, Peltier and Thomson effects. Thermoelectric devices have numerous advantages of being solid state device with no moving parts and require no maintenance. It provides noiseless operation and it offers light weight, compactness and hence, occupies small space [5]. The thermoelectric devices have better efficiencies at lower power levels compared with conventional thermodynamic devices used for power generation and space conditioning. Therefore, the thermoelectric devices are best suited for low power applications [6].

Thermoelectric heat pump (TEHP) works as a reversed heat engine operating between the two heat reservoirs as shown in Fig. 1 and its actual energy efficiency is lower than the ideal Carnot efficiency because of the irreversibilities induced by the electrical, thermal and the thermoelectric properties of the thermoelectric materials.

The thermoelectric heat pump systems can be used as cooler and/or heat pump by changing the direction of current flow through the thermoelectric couples. It does not require refrigerant to pump heat from the heat source to the heat sink since electrons serve this purpose. So there is no leakage of refrigerants and thus it does not contribute for ozone depletion and other environmental damages caused by the refrigerants as in conventional refrigerators. The thermal energy output of single thermoelectric couple is low and it can be increased to required level by adding several thermoelectric couples in series–parallel combination.

The efficiency of the thermoelectric devices depends on electrical conductivity (σ), thermal conductivity (k), and seebeck coefficient (α) of the thermoelectric material. The combination of these material properties of a thermoelectric material is defined as figure of merit (FOM) Rowe [3]. FOM is often defined as dimensionless figure of merit by multiplying it with mean operating temperature (T_m).

$$Z = \frac{\alpha^2 \sigma}{k} \tag{1}$$

$$ZT_m = \frac{\alpha^2}{\rho k} T_m \tag{2}$$

where, $T_m = \frac{T_H + T_C}{2}$ and symbols have their usual meanings.

To understand the reversible and irreversible effects in thermoelectric systems, one can classify them thermodynamically into four categories based on the irreversibilities in the system

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.03.069
0017-9310/

Nomenclature

A	area (m^2)
Ex	exergy (W)
I	current (A)
K	thermal conductance (W/K)
L	length (m)
P	electrical power (W)
Q	heat (W)
R	electrical resistance (Ω)
S	entropy (W/K)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2K)
V	voltage (V)
Z	figure of merit (1/K)

Greek letters

α	Seebeck coefficient (V/K)
η	energy efficiency
k	thermal conductivity (W/mK)
ρ	electrical resistivity (Ω/m)
σ	electrical conductivity (S/m)
Δ	difference
Ψ	exergy efficiency

Subscripts

1	hot junction of TEHP
2	cold junction of TEHP
ce	ceramic layer
d	destroyed
en	endoreversible TEHP
ex	exoreversible TEHP
gen	generation
hp	heat pump
in	input
ir	irreversible TEHP
lost	lost
m	mean temperature
n	*n* type material
o	environment
p	*p* type material
t	total
C	cold side of TEHP
H	hot side of TEHP
I	ideal TEHP
Qh	heating power

such as ideal (or) reversible system, exoreversible system, endoreversible system, and irreversible system as shown in Fig. 2. Thermoelectric devices always have internal irreversibilities because of the intrinsic material properties. Super conductors have very low electrical resistivity but its electrical/thermal conductivity is high, and its seebeck coefficient is also very small so its figure of merit is very low and hence, these may not be the potential thermoelectric materials. Therefore, the term "ideal thermoelectric system" may not be thermodynamically possible.

Cvahtet and Strnad [7] thermodynamically analysed the ideal thermoelectric heat engine and heat pump and compared it with the actual systems. Nuwayhid et al. [8] and Wang et al. [9] have analysed the thermoelectric system based on entropy generation minimization method. Sharma et al. [10] have carried out simple exergy analysis of single and multistage exoreversible thermoelectric cooling system. Tipsaenporm et al. [11] have proposed thermodynamic analysis in thermoelectric cooler and found out second law efficiency is less than the first law (energy) efficiency.

Exergy analysis provides true measure of efficiency since it takes into considerations of first and second law of thermodynamics. With this technique the actual exergy destruction is in the system can be located so that the avoidable exergy losses can be reduced by taking corrective actions [12–16].

Based on the literature survey, it is found that exergy analysis in thermoelectric heat pump systems are not been carried out. The effect of contact resistance and irreversible heat transfer in the exergy efficiency is also not been studied. Therefore it becomes necessary to carryout exergy analysis in the thermoelectric heat pump system. In this study the authors have developed four thermodynamic models of thermoelectric heat pump to identify and quantify the internal and external irreversibilities in view of the exergy analysis.

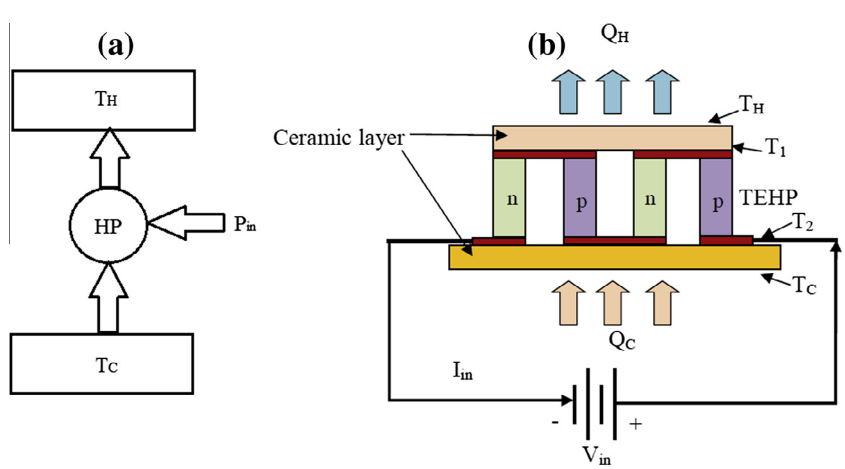

Fig. 1. (a) Reversed heat engine (Heat pump), (b) Thermoelectric heat pump.