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Review of Thermoelectric Devices for Cooling Applications

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ABSTRACT: Thermoelectric devices are solid-state devices. Semi-conductor thermoelectric power generation, based on the Seebeck effect, and semi-conductor thermoelectric cooling, based on the Peltier effect, have interesting capabilities compared to conventional power generation and cooling systems. The absence of moving components results in increase in reliability, a reduction in maintenance, and an increase of system life; the modularity allows for application in wide range without significant losses in performance; the absence of working fluid avoids environmental dangerous leakages; and the noise reduction appears also to be an important feature. With the rapid development of techniques to make excellent semi-conductor materials the practical applications and theoretical investigations of the thermoelectric devices have come into focus. This article begins with a brief overview of thermoelectric technology, thermoelectric materials, thermoelectric module construction and operation. A review of recent developments in research, commercial development, and typical applications of thermoelectric devices is made. The article draws conclusions on the development and potential application of thermoelectric devices suitable for thermoelectric cooling. **Keywords:** Thermoelectric technology; Power generation; Cooling applications; Seebeck effect; Peltier effect.

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I. INTRODUCTION

Thermoelectric coolers (TEC), also known as Peltier Coolers are solid-state heat pumps that utilizes the Peltier effect to move heat. The principle of thermoelectric cooling dates back to the discovery of the Peltier effect by Jean Peltier in 1834. Peltier observed that when electric current passes across the two junctions of two dissimilar conductors (a thermocouple) there was a heating effect that could not be explained by Joule heating alone. Infact, depending upon the direction of current, the overall effect could either be heating or cooling. This effect can be harnessed to transfer heat, creating a heater or cooler. Peltier himself did not appreciate the potential of his discovery, and it was not efficiently exploited until the end of the 20th century.

Paper is organized as follows. Section II describes automatic text detection using morphological operations, connected component analysis and set of selection or rejection criteria. The flow diagram represents the step of the algorithm. After detection of text, how text region is filled using an inpainting technique that is given in Section III. Section IV presents experimental results showing results of images tested. Finally, Section V presents conclusion.

II. HOW IT WORKS

When two conductors are placed in electric contact, electron flow out of one, in which the electrons are less bound, into the one where the electrons are more bound. The reason for this is a difference in the so-called Fermi level between the two conductors. The Fermi level represents the demarcation in energy with in the conduction band of a metal, between the energy level occupied and unoccupied energy levels. When two conductors with different Fermi levels make contact, electrons flow from the conductor with the higher level, until the change in electrostatic potential brings the two Fermi levels to the same value. Current passing across the junction results in either a forward or a reverse bias, resulting in temperature gradient. If the temperature of the hotter junction is kept low by removing the heat, the temperature of the cold plate can be cooled by tens of degrees.

A. Choosing Materials

At first glance, metals with their low electrical resistance might seem like a good choice for TEC construction; however, they also have high thermal conductivity. This tends to work against any heat gradient produced and lowers their



overall ZT (Z is figure of merit, T is operating temperature) value. In practice, semi-conductors are the material of choice. These are usually manufactured by either directional crystallization from a melt or pressed powder metallurgy. The thermoelectric semi-conductor material most often used for TEC is an alloy of Bismuth Telluride (Bi_2Te_3) that has been suitably doped to provide individual blocks or elements having distinct “n” and “p” characteristics. Other thermoelectric materials include Lead- Telluride (Pb-Te), Silicon-Germanium (Si-Ge), and Bismuth-Antimony (Bi-Sb) alloys, which may be used in specific situation.

B. TCE Construction

TEC are constructed using two dissimilar semi-conductors, n-type and p-type (in order to have different electron densities needed for better effect) (Figure 1). The two semi-conductors are positioned thermally in parallel and joined at one end by a conducting cooling plate (typically of copper or aluminium). A voltage is applied to the free ends of the two different conducting materials, resulting in a flow of electricity through the two semi-conductors in series. The flow of DC across the junction of the two semi-conductors creates a temperature difference. Giving rise to Peltier cooling and hence absorption of heat from the vicinity of the cooling plate. If the direction of current is changed by changing the polarity of the battery, the cold side becomes hot side and the hot side becomes cold side in TEC.

C. Analysis of Thermoelectric Systems

Whenever direct current passes through a pair of thermocouples with junction temperatures maintained at different temperatures, five effects are observed: Seebeck effect, Peltier effect, Thomson effect, Joulean effect, and Conduction effect.

Seebeck Effect; When two junctions of a pair of dissimilar metals are maintained at different temperatures, there is a generation of emf (electromotive force). A series of tests by varying the temperature of the junctions of various combinations of a set of materials were conducted and it was found that

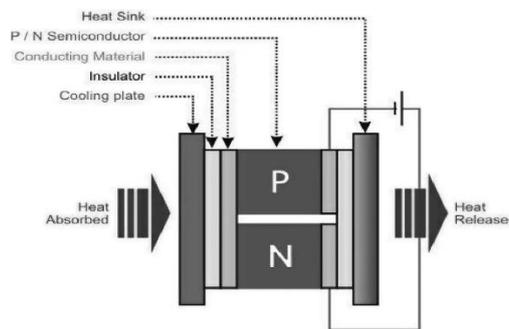


Fig.1.TEC construction.

$$E \propto T \quad (1)$$

where E and T are the emf output and the temperature difference of the junctions. The phenomenon of generation of emf is called Seebeck effect. The proportionality constant of Eq. (1)

$$\alpha_{ab} = E/T \quad (2)$$

and is called Seebeck coefficient. Seebeck coefficient is the property of a material that determines the performance ability of thermocouples. Here, $\alpha_{ab} = \alpha_a - \alpha_b$ is the coefficient for two different metals (A and B or p and n).

Peltier Effect; If the direct current is passed through a pair of dissimilar metals, there is a heating at one junction, cooling at the other depending upon material combinations. Peltier varied the current and observed the heating and cooling rate for different sets of elements.

It was found that:

$$Q \propto I \quad (3)$$

where Q is the cooling or heating rate. The proportionality constant for Eq. (3) is called Peltier coefficient, i.e.,

$$Q = abI \quad (4)$$

Where $ab = a - b$ is the coefficient for two different metals.



Thomson Effect; It is a reversible thermoelectric phenomenon. When a current passes through a single conductor having a temperature gradient, heat transfer is given by:

$$\frac{\delta Q}{\delta x} = \tau I \left(\frac{dT}{dx} \right) \quad (5)$$

where τ being Thomson coefficient, and $\delta Q/\delta x$, the Thomson heat transfer.

Using first and second law of thermodynamics a relation between Seebeck and Peltier coefficient can be established as:

$$ab = \alpha_{ab} T \quad (6)$$

$$\tau a - \tau b/T = d\alpha_{ab}/dT \quad (7)$$

Using Eqs. (6) and (4), it is found:

$$Q = \alpha_{ab} IT \quad (8)$$

This is clear from Eq. (8) that to get high Q, α_{ab} should be high otherwise large current will be required.

Joule Effect; When the electrical current flows through a conductor, there is dissipation of electrical energy. According to Joule it is related as:

$$Q_j = I^2 R \quad (9)$$

where I and R are the current and electrical resistance.

Conduction Effect; If the ends of any element are maintained at different temperatures, there is heat transfer from the hot end to the cold end and is related by:

$$Q_{cond} = U (T_h - T_l) \quad (10)$$

where U being overall conductance and T_h and T_l are high and low temperatures respectively.

If there is only one conductor of cross-sectional area A, conductivity K, and length L, the overall conductance is given by:

$$U = kA/L \quad (11)$$

D. Thermodynamic Analysis of Thermoelectric Refrigeration System

Fig (2) shows an enlarged view of thermoelectric element.

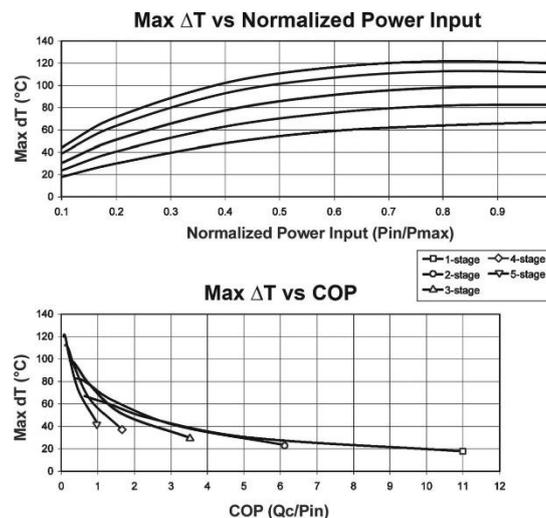


Fig.2. MaxT vs normalised power input and COP curve.

Cooling and heating due to the thermoelectric effect is given by:

$$Q_c = \alpha_{ab} IT_l \quad (12)$$



$$Q_h = \alpha_{ab} I T_h \quad (13)$$

Energy balance equations for hot and cold junctions can be written as:

$$Q_c = \alpha_{ab} I T_c - (I^2 R / 2) - U (T_h - T_c) \quad (14)$$

$$Q_h = \alpha_{ab} I T_h + (I^2 R / 2) - U (T_h - T_c) \quad (15)$$

Using first law, the energy input can be obtained as:

$$\oint Q = \oint W = -Q_h + Q_c = -[\alpha_{ab} I (T_h - T_c) + I^2 R] \quad (16)$$

where negative sign indicates that energy is supplied to the system. The required COP is:

$$COP = Q_c / W = [\alpha_{ab} I T_c - (I^2 R / 2) - U (T_h - T_c)] / [\alpha_{ab} I (T_h - T_c) + I^2 R] \quad (17)$$

COP is defined as the amount of heat absorbed at the cold side of the TEM (in thermal watts) divided by the input power (in electrical watts). Thermal watt is the heat absorbed at the cold side of peltier module, i.e., Q_c and electrical watt is the power supplied by the battery used in the circuit W .

III. BENEFITS OF TEC

While refrigerators and air-conditioners utilize compressors, condensers and refrigerants to lower temperature; solid-state cooling utilizes DC power, heat sinks and semiconductors. This fundamental difference gives solid-state TEC the following advantages over conventional devices.

Environment friendly (as no refrigerants are used). Therefore, leaking problem of refrigerants can also be avoided. As CFC's have high ozone depletion potential and HCFC's have comparatively low ozone depletion level, they are being phased out. In this situation TEC's can be the best alternate as it has zero harmful effect.

Can be manufactured in compact sizes using less space.

Lightweight, which can be advantageous where light weight is more important feature than COP. (e.g., in aviation).

Rate of refrigeration and COP can be easily controlled by varying voltage and current.

IV. STATE OF ART REVIEW

A. Performance Investigation

The novel concept of thermoelectric self-cooling introduced as a cooling and temperature control of a device using thermoelectric technology without electricity consumption was studied by Martínez, Astrain, and Rodríguez 2011. Various theoretical and experimental studies have been reported to evaluate and enhance the utility of TEC. The performance of a thermoelectric air-cooling module for electronic device was studied by Chang et al. 2009. It was shown that at a specific heat load, the thermoelectric cooling module reaches the best cooling performance at an optimum input current. An experimental investigation using a Peltier TEC to cool down a cryoprobe for cryosurgery was performed by Putra et al. 2010. Two prototypes of cryosurgery devices consisting of 5 to 6 stages of TEC modules were analyzed using a variety of electrical voltages. A model of thermoelectric generator driven thermoelectric refrigerator with external heat transfer was probed. The influence of the external and internal irreversibility of the thermoelectric refrigeration device on the performance of the system was analyzed (Pan, Lin, and Chen 2007; Chen, Meng, and Sun 2012a).

B. Power of TEC

Commercially available solid-state thermoelectric devices may be used for their electrical power generation capabilities when coupled to a thermometric refrigerator or heat pump. The DC current provided to run a thermoelectric refrigerator can be generated from solar cells also. Many researchers have done experimental investigation of a TEC coupled with a solar cell. A solar-driven thermoelectric cooling module with a waste heat refrigeration unit designed for green building application was investigated (Dai, Wang, and Ni 2003; Cheng, Meng, and Sun 2012a). It was found that the approach



was able to produce a 16.2°C temperature difference. TEC were found suitable for such applications where a precise control of temperature is required. An analysis of TEC performance was conducted for high-power electronic packages such as processors. The cooling capacity, junction temperature, COP of TEC, and the required heat sink thermal resistance at the TEC hot side were computed. Design and testing of a microprocessor controlled portable thermoelectric medical cooling kit was done (Güler and Ahiska 2002; Chein and Huang 2004; Zhang, Mui, and Tarin 2010).

C. TCE as a Hybrid System

Hybrid systems like thermoelectric system and vapor compression systems have also been tried by Vián and Astrain 2009 and Riffat and Guaquan 2004. The performance of three types of domestic air conditioners namely the vapor compression air conditioner (VCACs), the vapor absorption air conditioner (VAACs), and the thermoelectric air-conditioner (TEACs) was compared. The comparison showed that although VCACs have the advantages of high COP and low purchase price, use of these systems will be phased out due to their contribution to the greenhouse effect and depletion of ozone. VAACs are generally bulky, complex, and expensive but operate on thermal energy so their operational cost is low. TEACs are environment friendly, simple, and reliable but are still expensive. Their low COP is an additional factor. TEACs, however, have a large potential market as air-conditioner of small enclosures such as cars and submarine cabins.

D. Optimisation of TCE

To obtain an optimized performance from TEC various optimization techniques have been used to optimize the operational performance as well as their size. A general approach in evaluating and optimizing TEC performance was presented by Zhang in 2010. A numerical study on the performance of miniature TEC affected by Thomson effect was done (Du and Wen 2011; Chen, Meng, and Sun 2012a). With the help of optimal control theory, development of a sufficiently precise technique for computerized design of segmented TEC was done (Vikhor and Anatychuk 2006). Pérez-Aparicio, Palma, and Taylor 2012 did a finite element simulation of a commercial thermoelectric cell, working as a cooling heat pump. This analysis concludes that the temperature dependence of the materials properties of electric conductivity and Seebeck coefficient is very relevant on cell performance. Cooling capacity, coefficient of performance as well as the dimension of legs, leg area and number of legs of TEC were optimized using genetic algorithm (Cheng and Lin 2005; Cheng and Shih 2006). A model that was different from the other studies, in which the p-n pair was simply treated as a single bulk material was developed. In this model, the TEC was divided into four major regions, namely, cold end, hot end, p-type and n-type thermoelectric element (Cheng, Huang, and Cheng 2010). A new study in which Z , K , and R etc. parameters of standard TE module of Melcor Inc. had been acquired with a new computer-controlled system, Thermoelectric Performance Analysis System (TEPAS) by Ahiska, Dislitas, and Omer 2012. A temperature—entropy analysis was done, where the Thomson effect bridges the Joule heat and Fourier heat across the thermoelectric elements of a thermoelectric cooling cycle to describe the potential energy flows or performance bottlenecks or dissipations (Chakraborty et al. 2006). A generalized theoretical model was presented for the optimization of a thermoelectric cooling system in which the thermal conductance from the hot and cold sides of the system were taken into account by Zhou and Yu 2011. A detailed analysis of the optimal allocation of the finite thermal conductance between the hot side and cold side heat exchangers of the TEC systems were conducted considering the constraint of the total thermal conductance. The analysis showed that the maximum COP and the maximum cooling capacity of the TEC system can be obtained when the finite total thermal conductance is optimally allocated. Luo et al. 2003 applied the theory of finite time thermodynamics to analyse and optimize the performance of a thermoelectric refrigerator, which is composed of multiple elements.

E. Single-stage & Multi-stage TCE

TEC can work in single stage as well as in multistage configurations. A multistage thermoelectric module should be used only when a single stage module does not meet control temperature requirements. Figure 2 shows two graphs: the first plot gives the variation of T vs. Normalized Power input (P_{in}/P_{max}) of single and multistage modules. The second plot gives the variation of T vs. COP.

These figures should help one to identify when to consider cascades since they portray the effective T range of the various stages. A two-stage cascade should be considered somewhere between a T of 40°C and 65°C. Below a T of 40°C, a single stage module may be used, and a T above 65°C may require a 3, 4, or even 5 stage modules. A theoretical analysis and simulating calculations were conducted for a basic two-stage thermoelectric module, which contains one thermocouple in second stage and several thermocouples in the first stage. A pyramid-type multi-stage



cooler was analysed, focusing on the importance of maximum attainable target heat flux and over all coefficient of performance (Yu, Zhao, and Xie 2007; Yu and Wang 2009; Karimi, Culham, and Kazerouni 2011).

F. Feasibility Study of TCE

Various three-dimensional model studies and experimental investigations have been done to evaluate the feasibility of TEC. An experimental study was done to produce a portable solar still. The technique consists of using a solar collector, a wall covered with black wool and water, sprinkling system to increase evaporation rate, and a thermoelectric cooling device to enhance water condensation (Esfahani, Rahbar, and Lavvaf 2011). The feasibility study of using thermometric coolers in a dehumidification system to condense atmospheric moisture and generate renewable fresh water was done by Milani et al. 2011. A refrigerator system of thermoelectric refrigerator (TER; $25 \times 25 \times 35 \text{ cm}^2$) was fabricated by Jugsujinda, Vora-ud, and Seetaw (Casano and Piva 2011). A study was done to investigate the performance of a TEG combined with an air-cooling system designed using two-stage optimization. An analytical method was used to model the heat transfer of the heat sink and a numerical method with a finite element scheme was employed to predict the performance of the TEG (Wang, Hung, and Chen 2012). A concept of thermoelectric cogeneration system (TCS) was proposed to highlight the direction for enhancing the sustainability by improving the energy efficiency in domestic sector. Compared to the thermoelectric systems used in other areas which only uses the part of converted energy but wastes the unconverted part by dissipating it into the environment, the system presented here maximally recover the available heat by generating electrical power and producing hot water simultaneously (Zheng, Yan, and Simpson 2013).an 2011 using a TEC (TEC; $4 \times 4 \text{ cm}^2$). Numerical analysis has been carried out to figure out the performance of the thermoelectric micro-cooler with the three-dimensional model by Lee et al. 2007. A heat exchanger for the cold side of a Peltier pellets in thermoelectric refrigeration, based on the principle of a thermosyphon with phase change and capillary action was developed (Chen et al. 2002; Slaton and Zeegars 2006; Viánand Astrain 2008). It was found that the COP of the thermoelectric refrigerator can be improved up to 32% by incorporating the developed device. A model of thermoelectric generator-driven thermoelectric refrigerator with external heat transfer was proposed. The performance of the combined thermoelectric refrigerator device obeying Newton's heat transfer law was analysed using the combination of finite time thermodynamics and non-equilibrium thermodynamics (Chen, Meng, and Sun 2012a). An experimental investigation was carried out to characterize the performance of thermoelectric modules used for electric power generation over a range of different resistance loads. The performance of a Peltier cell used as a thermoelectric generator was evaluated in terms of power output and conversion efficiency. The results showed that a thermoelectric module is a promising device for waste heat recovery

V. CONCLUSION

Thermoelectric technology can be used in cooling, heating, and micro-power generation applications. Macro-thermoelectric devices have developed significantly since their introduction in the 1960's, and have achieved commercial success in mini-refrigeration, cooling, and space-craft power applications. There is a requirement to reduce the size, and improve the performance, of current thermoelectric devices in order to address the need to solve thermal problems. In the near future, thermoelectric devices will make a significant contribution, over a wide range of applications, in reducing fossil fuel consumption and global warming.

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