CHAPTER 2

REVIEW OF LITERATURE
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LITERATURE REVIEW

Thermoelectric coolers (TEC), also known as Peltier Coolers are solid state heat pumps that utilize 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. In fact, the direction of current decides the cooling effect or heating effect. This effect can be harnessed to transfer heat, creating a heater or cooler. Peltier could not realize the importance of this phenomenon and the other scientists also could not utilize this phenomenon till late 20th century. Thermoelectric technology, as one entirely solid state energy conversion way, can directly transform thermal energy into electricity and vice-versa by using thermoelectric transformation materials. A thermoelectric TEC has no moving parts, and is compact, quiet, highly reliable and environment friendly. Due to these merits, this technology is presently becoming a noticeable research direction. Bell (2008); Heremans et al. (2008); Poudel et al. (2008); Hochbaum et al. (2008); Boukai et al. (2008); Lyeo et al. (2004); Hsu et al. (2004)

2.1 Working of TEC

When the two ends of two dissimilar conductors are connected to a battery, electrons flow out of one in which the electrons are loosely bound to the one in which the electrons are tightly bound. This occurs due to the deference in the Fermi
level between the 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 the two different conductors are joined which have different Fermi levels, electron start flowing from the conductor with higher level to the other one. This flow continues till the electrostatic potential bridges this gap and the two Fermi levels come at 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.

2.2 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 semiconductor material most often used for TEC is an alloy of Bismuth Telluride (Bi₂Te₃) 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. There has been considerable interest in finding new materials and structures to use in clear, highly efficient cooling and energy conversion systems. Wood (1988); Mahan et al. (1997). The
increase in $ZT = \alpha^2 T/\rho k$, leads directly to the improvement in the cooling efficiency of Peltier modules and in the energy conversion efficiency of TEG. Goldshmidt (2004). Much effort has been made to raise $Z$ of TE materials using various methods so that there are improvements in $Z$ (for example, $3.2 \times 10^{-3} \text{ K}^{-1}$ at 300 K, $3.99 \times 10^{-3} \text{ K}^{-1}$ at 298 K, $3.70 \times 10^{-3} \text{ K}^{-1}$ at room temperature and $4.58 \times 10^{-3} \text{ K}^{-1}$ at 308 K for Bi-Te alloys.) Yim et al. (1972); Yamashita et al. (2003); Ettenberg et al. (1996); Yamashita et al. (2003).

2.3 TEC 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) Fig 2.1. The two semi-conductors are positioned thermally in parallel and joined at one end by a conducting cooling plate (typically of copper or aluminum). 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 semiconductors 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.
2.4 Thermoelectric Effect

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.

2.4.1 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
\[ \Delta E \propto \Delta T \]  \hspace{1cm} (1)

Where \( \Delta E \) and \( \Delta T \) are the emf output and the temperature difference of the junctions. This phenomenon of generation of emf is known as Seebeck effect. The proportionality constant of Eq.(1) \( \alpha_{ab} = \frac{\Delta E}{\Delta T} \)  \hspace{1cm} (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 & B or p and n)

2.4.2 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: \( Q \propto I \)  \hspace{1cm} (3)

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

\[ Q = \Pi_{ab} I \]  \hspace{1cm} (4)

Where \( \Pi_{ab} = \Pi_a - \Pi_b \) is the coefficient for two different metals.

2.4.3 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:
\[ \frac{\partial Q}{\partial x} = \partial \left( \frac{dT}{dx} \right) \]  

(5)

where \( \tau \) 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:

\[ \Pi_{ab} = \alpha_{ab} T \]  

(6)

\[ \frac{\tau_a - \tau_b}{T} = \frac{d\alpha_{ab}}{dT} \]  

(7)

Using Eq.6 and 4, it is found:

\[ Q = \alpha_{ab} IT \]  

(8)

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

2.4.4 Joulean effect

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

\[ Q_j = I^2 R \]  

(9)

Where I and R are the current and electrical resistance.
2.4.5 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:

\[ Q_{\text{cond}} = U(T_h - T_l) \]  \hspace{1cm} (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:

\[ U = \frac{kA}{L} \]  \hspace{1cm} (11)

2.5 Exergy

In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. Exergy is the energy that is available to be converted in form of useful energy. When the system reaches a state when it is in equilibrium with surroundings (called a dead state), the exergy is zero. Measurement of exergy is always of primary interest in thermodynamics. The word ‘exergy’ was first used by Zoran Rant (1904-1972) that combines two Greek words ‘Ex’ and ‘Ergon’ which means ‘from work’ but concept was built up by J. Willard Gibbs in 1873. Energy and exergy differ in their behavior as energy can never be created or destroyed but exergy is destroyed during a process due to irreversibilities and causes entropy generation. Therefore energy has two parts, one is available called ‘exergy’ and another which is not
available called ‘anergy’. In the field of thermal engineering exergy analysis is used as a tool to utilize energy in more efficient way. Exergy is a combined property of the system as well as surroundings as it includes the state of system and surroundings both.

Exergy is also known with similar names e.g. availability, available energy, utilizable energy, available useful work, maximum amount of (or minimum) work, reversible work, and ideal work.

In a cycle which includes number of processes, exergy destruction is calculated for each processes individually and then added for the entire cycle. Exergy destruction can also be determined by determining the entropy generation. Thermodynamic second law efficiency can be calculated with the help of exergy destruction or entropy generation which is the more authentic efficiency in comparison to the first law efficiency. Cengel et al. (1989)

2.6 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. Venkatasubramanain et al. (2001); Chen et al. (2010); Yamashita (2009); Yamashita (2008). This fundamental difference gives solid state thermoelectric coolers 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. It this situation TEC’s can be the best alternate as it has zero harmful effect.

- Can be manufactured in compact sizes using less space.
- Light weight, which can be advantageous where light weight is more important feature than COP (e.g. in aircrafts).
- Rate of refrigeration and COP can be easily controlled by varying voltage and current.

2.7 STATE OF THE ART REVIEW

It is as follows:

2.7.1 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 et al., 2011. Various theoretical and experimental studies have been reported to evaluate and enhance the utility of thermoelectric coolers. 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 thermoelectric cooler 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 irreversibilities of the thermoelectric refrigeration device on the performance of the system was analyzed (Chen et al., 2011, Pan et al., 2007).

2.7.2 Power for 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 et al., 2003, Cheng et al., 2011). It was found that the approach was able to produce a $16.2^\circ$C temperature difference. Thermoelectric coolers 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 (Zhang et al., 2010, Güler and Ahiska, 2002, Chein and Huang, 2004).
2.7.3 TEC as a Hybrid System

Hybrid systems like thermoelectric system and vapor compression systems have also been tried by Vián and Astrain, 2009. 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 green house 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. In recent years much researchers have done more work in thermoelectric cooling. (Min et al., 1999; Khedari et al., 2001; Chen et al., 1996)

2.7.4 Optimization of TEC

To obtain an optimized performance from thermoelectric cooler various optimization techniques have been used to optimize the operational performance as well as their size. A general approach in evaluating and optimizing thermoelectric cooler performance was presented by Zhang in 2010. A numerical study on the performance of miniature thermoelectric cooler affected by Thomson effect was done (Chen et al., 2012, Du and Wen, 2011). With the help of optimal control theory, development of a sufficiently precise technique for computerized design of
segmented thermoelectric coolers was done (Vikhor and Anatychuk, 2006). Pérez–Aparicio et al., 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 Shih, 2006, Cheng and Lin, 2005). A model which 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 thermoelectric cooler was divided into four major regions, namely, cold end, hot end, p type and n type thermoelectric element (Cheng et al., 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 et al., 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 conductances from the hot and cold sides of the system were taken in to 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 analyze and optimize the performance of a thermoelectric refrigerator, which is composed of multiple elements. In general, conventional non-equilibrium thermodynamics is used to analyze the performance of single stage one or multiple element thermoelectric generators. Susman et al. (1995); Chen et al. (1996); Chen et al. (1997); Rowe et al. (1998); Omer et al. (1998); Mayergoyz et al. (1001); Naji et al. (2003); Nuwayhid et al. (2005); Chen et al. (2007); YU et al. (2007). The theory of finite time thermodynamics or entropy generation minimization is also a powerful tool for the performance analysis and optimization of practical thermodynamic process and devices. Andresen (1983); Andresen et al. (1984); Sieniutycz et al. (1990); Devos (1992); Sieniutycz et al. (1994); Bejan (1996); Hoffmann et al. (1997); Beery et al. (1999); Chen et al. (1999); Gordon (2000); Chen et al. (2004). Some authors have investigated the performance of thermoelectric generators and coolers using of finite time thermodynamics as well as non-equilibrium thermodynamics. Sun et al., (1990); Sun et al. (1993); Gordon (1991); Wu (1993); Wu (1993&1996); Agarwal et al. (1997); Chen at al. (1996, 1997 & 2000); Xuan et al. (2002) and Nuwayhid et al. (2003) analyzed the effect of finite rate heat transfer between the thermoelectric device and its external heat reservoirs on the performance of single-element single-stage thermoelectric generators. Chen et al. (2000, 2002 & 2004) and Crane et al. (2004) investigated the characteristics of single stage thermoelectric generators which has number of elements with the irreversibility due to finite rate heat
transfer. Effect of Joulean heat inside the thermoelectric device and the heat leak through the thermometric couple element was also considered.

2.7.5 Single-stage and Multi-stage TEC

Thermoelectric coolers can work in single stage as well as in multistage configurations. A multistage thermoelectric device should be used only when a single stage device is not able satisfy temperature control requirements. Fig 2.2 shows two graphs: the first plot gives the variation of temperature difference vs. normalized power input of single and multistage devices. The second plot gives the variation of $\Delta T$ vs. COP. These figures should help one to identify when to consider cascades since they portray the effective $\Delta T$ range of the various stages. A two-stage cascade should be considered somewhere between a $\Delta T$ of 40°C and 65°C. Below a $\Delta T$ of 40°C, a single stage module may be used, and a $\Delta T$ 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 multistage cooler was analyzed, focusing on the importance of maximum attainable target heat flux and over all coefficient of performance (Yu et al., 2007, Yu and Wang, 2009, Karimi et al., 2011).
2.7.6 Feasibility Study of TEC

Various three dimensional models studies and experimental investigations have been done to evaluate the feasibility of thermoelectric coolers. 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 et al., 2011). The feasibility study of using thermometric coolers in a dehumidification system to condense atmospheric moisture and generate renewable fresh water was done by Milan et al., 2011. A refrigerator system of thermoelectric refrigerator (TER; 25x25x35 cm$^3$) was fabricated by Jugsujinda et al., 2011 using a thermoelectric cooler (TEC; 4x4 cm$^2$). Numerical analysis has been carried out to figure out the performance of the thermoelectric micro-cooler with the three dimensional design 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 (Vian and Astrain, 2008, Slaton and Zeegars, 2006, Chen et al., 2002). 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 analyzed using the combination of finite time thermodynamics and non-equilibrium thermodynamics. Chen et al (2012). 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. Casano et al (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. WangChien et al (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. In comparison to the thermoelectric systems used in the areas where the part of converted energy is being used and unconverted part is discharged to the environment, a system was developed which recovers the available part of energy by producing electrical power and hot water from unavailable part. Therefore it utilizes the energy completely without wastage. Zheng et al (2013). Recently there is an increasing interest in the use of TEC for enhanced cooling of high power components like microprocessors in both manufacturing test process and user conditions. High cooling capacity TECs, in combination of air cooling or liquid cooling techniques, were persuaded to extend the conventional air cooling limits for high power dissipating microprocessors (Bierschenk et al., 2004; Bierschenk et al., 2006; Chen et al., 2004; Hasan et al., 2007; Pehlan et al., 2002).

2.8 Thermoeconomics

Thermoeconomics, as an exergy-aided cost reduction method, provides important information for the design of cost effective energy conversion systems. The exergy costing principle is used to assign monetary values to all material and energy streams within a system as well as the exergy destruction within the system.
The design evaluation and optimization is based upon the trade-off between exergy destruction (exergic efficiency) and investment cost. It is observed that in most of the studies (Adnan, 2001; Aprea et al, 2002; Adnan et al., 2003; Aprea et al., 2004; Adnan et al., 2007; Kabul et al., 2008; Ozkaymak et al., 2008; bayrakci et al., 2009; Kizilkan et al., 2010; Variyelni et al., 2011), performance comparison and performance analysis of refrigeration system is performed using energy approach based on first law and exergy analysis based on second law. Energy and exergy approaches are generally well known approaches, used to analyze thermal processes. Researchers who are working rigorously in the design of energy transformation plants and are willing to improve the first in hand design are keen to find out the answers of following questions:

1. What are the basic causes of thermodynamic inefficiencies in the system and how significant are they?
2. What measures should be taken or what may the alternative changes in the designs that would improve the efficiency of the overall plant?
3. How much is the total required investment and the total equipment cost of the plant?
4. How much do the thermodynamic inefficiencies cost the plant operator?
5. What measures should be taken to improve the cost effectiveness of the overall plant?

The answer to the first questions is provided with the aid of an energy and exergy analysis. An economic analysis answers the third question. The last two questions can be answered with the aid of a thermoeconomic analysis. This analysis is called
exergoeconomics, which is a more precise characterization of every exergy-aided cost reduction approach. A detailed study of thermoeconomics is found in Bejan et al. (1996); El-Sayed (2003). Exergoeconomics applied to the design optimization represents a unique combination of exergy analysis and cost analysis, to provide the designer of an energy conversion plant with information not available through conventional energy, exergy or cost analysis, but crucial to the design of cost-effective plant. Design optimization of energy conversion system means the selection of structure and the design parameters (the design variables) of the system to minimize the total cost of the system products (over the entire lifetime of the system) under boundary conditions associated with available materials, financial resources, environmental protection and government regulation as well as the safety, reliability, operability, maintainability and availability of the system. A thermodynamic optimization, which aims at minimizing the thermodynamic inefficiencies, represents a sub case of the general case of design optimization. An appropriate formulation of the optimization problem is always one of the most important and sometimes the most difficult task in the optimization study. There are various terminologies and names given to various exergoeconomic approaches presented in the past by researchers in previous years.

These names include the following:

- Exergy Economic Approach (EEA)
- First Exergoeconomic Approach (FEA)
- Thermoeconomic Functional Analysis (TEA)
- Exergetic Cost Theory (ECT)
• Engineering Functional analysis (EFA)
• Last-in-First Out Approach (LIFOA)
• Structural Analysis Approach (SAA)
• SPECO Method (SPECOM)

2.9 Recent Developments in Thermoelectrics

A computational model was developed by Martínez et al. (2013) for thermoelectric self-cooling applications, capable of simulating both the steady and the transient state of the whole system. This system was supported by fluid dynamics software and was based on implicit finite differences. This model was able to solve the system equations which involved Fourier’s law, thermoelectric effects Seebeck, Peltier, Joule and Thomson and the properties which are dependent on temperature difference. This model also has the capability to handle the new analytical expressions and functions to simulate any other component of the system which is more precision or has more complex design.

Ming & Jianlin (2013) presented a comprehensive analysis of a novel two-stage cascade thermoelectric cooler (TTEC). The novel TTEC was formed by joining short-legged thermoelectric couples in cascade, which had advantages of no interstage electrical insulating materials, compact and easy-fabricated structure, and used only one operating power. An analytical model taking into account the allocation of the total input current between the two stages of the TTEC was developed and the performance characteristics were investigated in detail.

Lin et al. (2013) studied on the optimal heat exchanger configuration of a TEC system. The effects of total heat transfer area allocation ratio, thermal conductance
of the TEC hot and cold side and TEM element material properties on the cooling performance of the TEC were investigated in detail based on the developed mathematical model. The analysis results indicate that the highest coefficient of performance (COP), highest heat flux pumping capability of the TEC and lowest cold side temperature can be achieved by selecting an optimal heat transfer area allocation ratio. Huang et al. (2013) developed an inverse problem approach to optimize the geometric structure of TECs (thermoelectric coolers).

Teaching–learning-based optimization (TLBO) is a recently developed heuristic algorithm based on the natural phenomenon of teaching–learning process. In the present work, a modified version of the TLBO algorithm was introduced by Rao & Patel (2013) and applied for the multi-objective optimization of a two stage thermoelectric cooler (TEC).

Temperature increment is one of the main challenges for solar concentrating photovoltaic systems which causes significant reduction in the cell efficiency and accelerates cell degradation. To overcome this issue, a novel cooling method by using Peltier effect was proposed and investigated by Najafi & Woodbury (2013). In this approach, a thermoelectric cooling module was considered to be attached to the back side of a single photovoltaic cell. A detailed model was developed and simulated via MATLAB in order to determine the temperatures within the system, calculate the required power to run the thermoelectric cooling module was calculated and the extra generated power by photovoltaic cells due to the cooling effect was done.
A theoretical investigation to optimize thermoelectric cooling modules was performed using a novel one dimensional analytic model by Jeong (2014). In the model the optimum current, which maximizes the COP of a thermoelectric cooling module, was determined by the cooling capacity of a thermoelement, the hot and cold side temperatures, the thermal and electrical contact resistances and the properties of thermoelectric material, but not by the length of a thermoelement.

The application of a TEG (thermoelectric power generator) to harvest energy from the waste heat of a commercial table lamp was investigated experimentally as well as numerically by Weng & Huang (2014). The table lamp was integrated with TEG chips which were cooled by a natural convection heat sink. Possible use of a novel portable desalination system was investigated experimentally by Yildirim et al. (2014). The system was based on humidification–dehumidification principle and thermoelectric cooling technique. A thermoelectric cooler was combined into the system to increase humidification and dehumidification processes.

Theoretical and experimental investigations of the winter operation mode of a thermoelectric cooling and heating system driven by a heat pipe photovoltaic/thermal (PV/T) panel was done by He et al. (2014). And the energy and exergy analysis of this system in summer and winter operation modes were also done.

A feasibility study was performed by Suh et al. (2014) applying a thermoelectric device to the energy storage system of an electric vehicle. A thermoelectric module was used for a lithium family battery system for controlling the cooling and pre-heating of the battery and to recover the energy which is being wasted.
Geometric design of an integrated thermoelectric generation-cooling system was performed numerically by Chen et al. (2014) using a finite element method. In the system, a thermoelectric cooler (TEC) was powered directly by a thermoelectric generator (TEG). Two different boundary conditions in association with the effects of contact resistance and heat convection on system performance were taken into account.

A multi-objective and multi-parameter optimization was implemented by Meng et al. (2014) to design the optimal structure of bismuth-telluride-based TEG (thermoelectric generator) module. A multi-physics TEG model combining the SCG (simplified conjugate-gradient) algorithm was used as the optimization tool. A thermoelectric generator must be designed keeping all geometric features in to account to enhance the performance such as efficiency and power output. A study has been done in which three the-state-of-the-art multi-objective evolutionary algorithms, namely, NSGA-II (Non-dominated Sorting Genetic Algorithm-II), GDE3 (Generalized Differential Evolution generation 3), and SMPSO (Speed-constrained Multi-objective Particle Swarm Optimization) are used to optimize the geometric features of a thermoelectric generator to improve its efficiency and power output when it is operating in different conditions. Geometric parameters may be defined shape factor and size of pin length and the operating parameters may be defined as temperature ratio and load on thermoelectric cooler. A thermal investigation has been done by taking the geometric and operating features in to account. The findings were also validated with a practical system. It was reported in
the literature that pin size and shape factor both have noticeable impact on the performance of the device. If the shape factor is increased, it initially increases the thermal efficiency up to a maximum value but the further increase in shape factor deteriorates the thermal efficiency. The power output from the module behaves differently. It increases initially with the increment in the shape factor but then no effect is registered in power out with further increment of shape factor. A new designed was presented for a specific operating conditions for a thermoelectric power generation module to give maximum thermal efficiency and power output. Ibrahim et al. (2014). An ideal heat exchanger should recover as much heat as possible from an engine exhaust at the cost of an appreciable pressure drop. The primary heat is provided to thermoelectric generator (TEG), and their capacity and efficiency is dependent on the physical properties of the element like material, shape, and type of the heat exchanger.

Six different exhaust heat exchangers were investigated within the same shell, and their computational fluid dynamics (CFD) models were developed to compare heat transfer and pressure drop in typical driving cycles for a vehicle with a petrol engine. The result showed that the serial plate structure enhanced heat transfer with the help of baffles and the rate of heat transfer was maximum. It also produced a significant pressure drop of in a suburban driving cycle. The numerical results for the pipe structure and an empty cavity were also validated with the help an experiment setup. Bai et al., 2014. A study has been done by combining thermionic-thermoelectric refrigerator which has a finite rate heat transfer. In this
study expressions were derived for rate of heat transfer and coefficient of performance, the most important parameters for a refrigeration system.

The performance of the irreversible combined refrigerator, in which the heat transfer between the device and the heat reservoir obeys Newton's heat transfer law, was analyzed and optimized by using the combination of finite time thermodynamics and non-equilibrium thermodynamics. The impact of external heat transfer was reported by comparing the behavior of irreversible combined refrigerator with the conventional analysis without heat transfer losses. The behavior of the combined refrigerator device with external heat transfer was further compared with those of an independent vacuum thermionic refrigerator with and without considering external heat transfer. Moreover, for the fixed total heat transfer surface area of four heat exchangers, the allocations of the heat transfer surface area among the four heat exchangers are investigated for maximizing the cooling load and the COP. The effect of total heat transfer surface area on the optimum performance of the irreversible refrigerator was explored with the help of numerical analysis of modules. The results obtained are helpful to provide guidelines for the design and application of a practical combined thermo-ionic and thermoelectric refrigeration devices. Ding et al (2014).

A study was reported with three-dimensional multi-physics model to optimize the performance of three kinds of multi-stage thermoelectric coolers, connected electrically in series, in parallel, and separated, respectively. The optimizations were performed for the two-stage thermoelectric coolers with number of thermoelectric elements. The number ratio and current ratio were investigated to
reach the optimal rate of refrigeration, coefficient of performance, and maximum
temperature difference, respectively. A significant temperature distribution was
observed for the two-stage thermoelectric cooler with number ratio larger or
smaller 1.00. In addition, the properties which are dependent on temperature were
proven to be extremely important for predicting the two-stage thermoelectric cooler
performance. Thermal resistance models extensively adopted in the previous two-
stage thermoelectric cooler studies could not predict the two-stage thermoelectric
cooler performance accurately because they assume the one-dimensional
temperature distribution and constant material properties. The results also show that
the thermoelectric element number on the hot stage should be larger than that on
the cold stage for improving the cooling capacity and COP. It was also reported that
the performance can be improved by applying the different amount of current in
two stages. Wang et al. (2014)

A theoretical model was developed for evaluating the efficiency of concentrating
photovoltaic thermoelectric hybrid system. Hybrid systems with different
photovoltaic cells was studied, that includes crystalline silicon photovoltaic cell,
silicon thin-film photovoltaic cell, polymer photovoltaic cell and copper indium
gallium selenide photovoltaic cell. The effect of temperature on the efficiency of
photovoltaic cell was taken into account based on the semiconductor expressions,
which showed different efficiency temperature behavior of polymer photovoltaic
cells. It was demonstrated that the polycrystalline silicon thin-film photovoltaic cell
is suitable for concentrating photovoltaic thermoelectric hybrid system. With the
help of optimization of the convection heat transfer coefficient and concentrating
ratio, the polymer photovoltaic cell is proved to be suitable for non-concentrating photovoltaic thermoelectric hybrid system. Zhang et al. (2014).

A combined thermal system consisting of a thermoelectric generator and a refrigerator was considered and the effect of location of the thermoelectric generator, in the refrigeration cycle, on the performance characteristics of the combined system was investigated. The operating conditions and their influence on coefficient of performance of the combined system were examined through introducing the dimensionless parameters, such as $k = Q_{\text{HTE}} / Q_{\text{H}}$, where $Q_{\text{HTE}}$ is heat transfer to the thermoelectric generator from the condenser, $Q_{\text{H}}$ is the total heat transfer from the condenser to its ambient), temperature ratio ($h_{\text{L}} = T_{\text{L}} / T_{\text{H}}$, where $T_{\text{L}}$ is the evaporator temperature and $T_{\text{H}}$ is the condenser temperature), $r_{\text{C}}$ ($r_{\text{C}} = C_{\text{L}} / C_{\text{H}}$, where $C_{\text{L}}$ is the thermal capacitance due to heat transfer to evaporator and $C_{\text{H}}$, is the thermal capacitance due to heat rejected from the condenser), $h_{\text{W}}$ ($h_{\text{W}} = T_{\text{W}} / T_{\text{H}}$, where $T_{\text{W}}$ is the ambient temperature), $h_{\text{C}}$ ($h_{\text{C}} = T_{\text{C}} / T_{\text{H}}$, where $T_{\text{C}}$ is the cold space temperature). It was found that the location of the thermoelectric generator in between the condenser and the evaporator decreases coefficient of performance of the combined system. Alternatively, the location of thermoelectric device in between the condenser and its ambient enhances coefficient of performance of the combined system. The operating parameter has significant effect on the performance characteristics of the combined system. Bekir et al. (2014).

Three different methods for predicting the Seebeck coefficient and power generation of a commercial available thermoelectric cooler module were used and compared to the experimental data. First method and second method were
developed based on mathematical models and third method was established in terms of experimental measurements. Method 3 considers the effect of cooling condition, whereas Method 1 and 2 did not. Two different temperatures at the cold side of the thermoelectric cooler module were also considered to account for the influence of cooling condition on the performance of the thermoelectric cooler. The power generation of the thermoelectric cooler module with low-temperature cooling is at least 5% higher than that with normal cooling. Method 3 gives the best prediction in open circuit voltage and power generation. Basically, the three methods are able to evaluate the properties and performance of a TEC easily, thereby providing useful tools for designing and constructing a TE generation system. Chen et al. (2015).

Energy crisis and environment deterioration are two major problems for 21st century. Thermoelectric device is a promising solution for those two problems. This review begins with the basic concepts of the thermoelectric and discusses its recent material researches about the figure of merit. It also reports the recent applications of the thermoelectric generator, including the structure optimization which significantly affects the thermoelectric generator, the low temperature recovery, the heat resource and its application area. Then it reports the recent application of the thermoelectric cooler including the thermoelectric model and its application area. It ends with the discussion of the further research direction. Wei et al. (2015).

A study was presented to a comprehensive thermodynamic modeling of a novel portable solar still through the first and second laws (of thermodynamics) analysis. In the new solar still, a thermoelectric module was employed to increase the
temperature difference between evaporating and condensing zones. Energy and exergy balance equations were written for all components of the solar still including glass cover, thermoelectric module, saline water, and basin-liner. A new approach has been used to evaluate evaporative heat transfer coefficients. Comparison of distilled water calculated by the present approach and the results obtained by employing various semi-experimental models proved the accuracy of the proposed thermodynamic modeling. It was also found that the exergy stored within the body of saline water, which was neglected in the most previous studies, is important and should be considered. It was shown that the daily average energy and exergy efficiencies of the solar still are around 20% and 1%, respectively. It was also reported that the exergy efficiency is much lower than the energy efficiency. It was observed that the rate of exergy destructions in solar still components is proportional to the incident solar intensity. The largest exergy destruction belongs to the thermoelectric module, which is 64% of the total exergy destruction, while the glass cover has the smallest share. It is concluded that although the energy efficiency associated with this type of thermoelectrically assisted solar still is higher than it’s the other options like simple passive solar still one, however, its exergy efficiency is lower. Dehghan et al. (2015).
2.10 Gaps and Opportunities:

1. Second Law Analysis of thermoelectric devices is required to understand their potential to serve the desired purposes.

2. Optimized operating condition should be evaluated to improve the performance.

3. Optimized design should be developed to enhance the application of thermoelectric devices where size, weight and shape are more important than efficiency or COP.