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Review on Thermoelectric Refrigeration: Applications and Technology

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Abstract— Refrigerator and air conditioners are the most energy consuming home appliances and for this reason many researchers had performed work to enhance performance of the refrigeration systems. Most of the research work done so far deals with an objective of low energy consumption and refrigeration effect enhancement. Thermoelectric refrigeration is one of the techniques used for producing refrigeration effect. Thermoelectric devices are developed based on Peltier and Seebeck effect which has experienced a major advances and developments in recent years. The coefficient of performance of the thermoelectric refrigeration is less when it is used alone, hence thermoelectric refrigeration is often used with other methods of refrigeration. This paper presents a review of some work been done on the thermoelectric refrigeration over the years. Some of the research and development work carried out by different researchers on TER system has been thoroughly reviewed in this paper. The study envelopes the various applications of TER system and development of devices. This paper summarizes the advancement in thermoelectric refrigeration, thermoelectric materials, design methodologies, application in domestic appliances and performance enhancement techniques based on the literature.

Keywords- Thermoelectric module, Peltier effect, Figure of Merit, Device Design Parameter, Seebeck coefficient, Coefficient of performance.

I. INTRODUCTION

Refrigeration means removal of heat from a substance or space in order to bring it to a temperature lower than those of the natural surroundings. Thermoelectric cooling is a way to remove thermal energy from a medium, device or component by applying a voltage of constant polarity to a junction between dissimilar electrical conductors or semiconductors. Thermoelectric Refrigeration provides cooling effect by using thermoelectric effect i.e. Peltier effect rather than the more prevalent conventional methods like those using the ‘vapor compression cycle’ or the ‘gas compression cycle’. [1]

Thermoelectric Refrigeration finds applications in electronic systems and computers to cool sensitive components such as power amplifiers and microprocessors. TER can also be used in a satellite or space application to control the extreme temperatures that occur in components on the sunlit side and to warm the components on the dark side. In scientific applications like digital cameras and charge-coupled devices (CCDs) TER is used to minimize thermal noise, thereby optimizing the sensitivity and image contrast.

The coefficient of performance (COP) of compression refrigerators decreases with the decrease in its capacity. Therefore, when it is necessary to design a low capacity refrigerator, TER is always preferable. Also, better control over the space temperature is the major advantage of the TER. Hence, TER is good option for food preservation applications & cooling of pharmaceutical products. [2]

Nomenclature:

A	Heat exchanger area [m^2]
COP	Coefficient of Performance
DC	Direct Current
h	Heat transfer coefficient [Wm^{-2}K^{-1}]
I	Current [A]
K	Conduction heat transfer coefficient [Wm^{-1}K^{-1}]
P	Input power [W]
Q	Rate of heat transfer [W]
R	Total electrical resistance [Ω]
S	Cycle irreversibility parameter
T	Absolute temperature [^{0}C]
TER	Thermoelectric Refrigeration
V	Voltage [V]
VCR	Vapour Compression Refrigeration
X	Device-design parameter
Z	Figure of merit [1/K]

Subscripts

C	Cold junction side
H	Hot junction side
L	Heat Source
W	Heat sink

Greek Letters

α	Seebeck coefficient [VK^{-1}]
β	Ratio of $h_H A_H$ *to* $h_L A_L$
τ	Ratio of T_L to T_H
ψ	Ratio of T_L to T_W
ϕ	Dimensionless refrigeration effect

A. *History*

Thermoelectricity was discovered and developed in 1820-1920 in Western Europe, with much of work centered in Berlin. The first important discovery related to thermoelectricity occurred in 1823. German scientist Thomas Seebeck [3] found that a circuit made from two dissimilar metals and junctions of the same kept at two different temperatures, produces thermoelectric force which is responsible for flow of the current through module. Now this invention is known as Seebeck effect. [3]

In 1834, a French watchmaker and physicist, Jean Charles Athanase Peltier [4] invented thermoelectric cooling effect also known as Peltier effect. Peltier stated that electric current flows through two dissimilar metals would produce heating and cooling at the junctions. [4]

The true nature of Peltier effect was made clear by Emil Lenz [5] in 1838, Lenz demonstrated that water could be frozen when placed on a bismuth-antimony junction by passage of an electric current through the junction. He also observed that if the current was reversed the ice could be melted. In 1909 and 1911 Altenkirch [6] give the basic theory of thermoelectric. His work explained that thermoelectric cooling materials needed to have high Seebeck coefficients, good electrical conductivity to minimize Joule heating, and low thermal conductivity to reduce heat transfer from junctions to junctions. In 1949 Loffe [7] developed theory of semiconductors thermo-elements and in 1954 Goldsmid [8] and Douglas [8] demonstrated that cooling from ordinary ambient temperatures down to below 0°C was possible. Rowe, [9] shortly after the development of practical semiconductors in 1950's, Bismuth Telluride began to be the primary material used in the thermoelectric cooling. [10]

II. MATERIAL REVIEW

Thermoelectric module is made of two different semiconducting materials, which generate thermoelectric cooling effect (Peltier effect) when a voltage of similar polarity & in appropriate direction applied through the connected junction. Two heat sinks & fans are attached to hot and cold sides of thermoelectric module in order to enhance heat transfer and system performance. There exists an optimum current & optimum voltage for maximum coefficient of performance (COP) for a specific module and fixed hot/cold side temperatures.

According to the primary criterion of figure of merit ($Z = \frac{\alpha^2}{RK}$), a good thermoelectric material should have high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. Commonly used thermoelectric materials are Bismuth Telluride (Bi_2Te_3), Lead Telluride (PbTe), Silicon Germanium (SiGe) and Cobalt Antimony ($CoSb_3$), among which Bi_2Te_3 is the most commonly used one. These materials usually process a *ZT* value (figure of merit at temperature) less than one. From 1960s to 1990s, developments in materials in the view of increasing *ZT* value was modest, but after the mid-1990s, by using nano structural engineering thermoelectric material efficiency is greatly improved. Thermoelectric materials such as primary bulk thermoelectric materials like skutterudites, clathrates and half-Heusler alloys, which are principally produced through doping method are developed but not exploited for commercial use. [11]

The best commercial thermoelectric materials currently have *ZT* values around 1.0. The highest *ZT* value in research is about 3. Other best reported thermoelectric materials have figure-of-merit values of 1.2-2.2 at temperature range of 320-520^{0}C. It is estimated that thermoelectric coolers with *ZT* value of 1.0 operate at only 10% of Carnot efficiency. Some 30% of Carnot efficiency could be reached by a device with a *ZT* value of 4. However, increasing *ZT* to 4 has remained a formidable challenge. Bell also mentioned that if the average *ZT* reaches 2, domestic and commercial solid-state heating, ventilating and air-cooling systems using thermoelectric material would become practical. [11]

Figure 1 [12]shows the *ZT* characteristics of common thermoelectric materials.

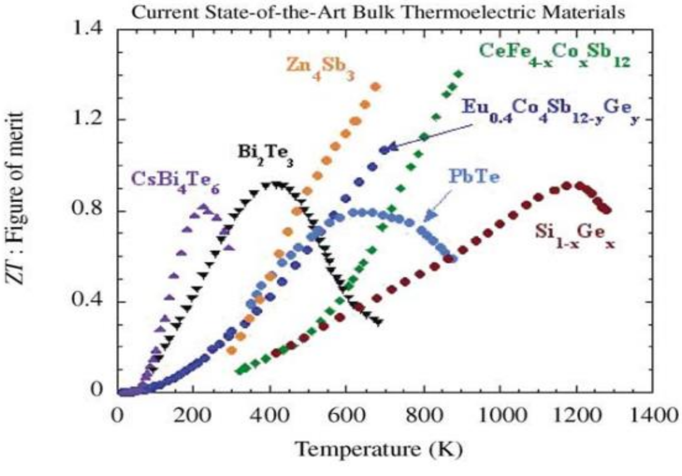


Figure 1 ZT Characteristics of diiferent TE Materials

III. DESIGN CONSIDERATION FOR TER

A system design method of thermoelectric cooler is developed in the present study. The design calculation utilizes the performance curve of the thermoelectric module that is determined experimentally. An automatic test apparatus was designed and built to illustrate the testing method. The performance test results of the module are used to determine the physical properties and derive an empirical relation for the performance of thermoelectric module. The thermal resistance of heat sink is chosen as one of the key parameters in the design of a thermoelectric cooler. An optimal design of thermoelectric cooler at the conditions of optimal COP is also studied. The optimal design can be made either on the basis of the maximum value of the optimal cooling capacity, or on the basis of the best heat sink technology available. [13]

Methodology

The theoretical equations for the thermoelectric module performance include:
The voltage equation,

$$V = \alpha(T_H - T_L) + IR \tag{1}$$

The input power equation,

$$P = \alpha I(T_H - T_L) + I^2R \tag{2}$$

The cooling capacity equation,

$$\dot{Q}_L = I\alpha T_C - K(T_H - T_L) - 0.5I^2R \tag{3}$$

The total heat rejection equation,

$$\dot{Q}_H = I\alpha T_W - K(T_H - T_L) + 0.5I^2R \tag{4}$$

And COP is given by,

$$COP = \frac{Q_L}{P} \tag{5}$$

An important physical property for the thermoelectric module is the figure of merit Z which is given by,

$$Z = \frac{\alpha^2}{RK} \tag{6}$$

The thermoelectric cooler can be designed at maximum COP or at maximum cooling capacity. In many applications, the thermal efficiency is more important. Thus, the design based on the maximum COP is adopted in the present study. [13]

Goktun [14] showed that heat transfer at a finite rate and electrical resistive losses are necessarily irreversible processes and unavoidable in a thermoelectric device. It is shown that the internal and external irreversibility in a thermoelectric refrigerator may be characterized by a single parameter, named the device-design parameter. The presence of this parameter in the equations for the refrigeration effect and the maximum input power shows that a real refrigerator has a smaller cooling capacity and needs more input power than an ideal refrigerator. [14]

The thermoelectric refrigerator circuit is shown in Figure 2 [14] for steady state conditions, the heat flow rate from the low temperature reservoir at T_L to the cold junction at T_c can be written as:

$$\dot{Q}_L = h_L A_L(T_L - T_C) \tag{7}$$

Similarly, on the high temperature side, the heat flow rate is:

$$\dot{Q}_H = h_H A_H(T_W - T_H) \tag{8}$$

Where h is the heat transfer coefficient, A is the heat exchanger surface area; T_w and T_H is the hot junction and sink temperatures respectively. Assuming all material properties, including the Seebeck coefficient (α), of the thermoelectric element is independent of temperature. A one-dimensional heat conduction analysis in the direction of current (I) flow yields the net rates of heat input and heat rejection as:
From the first law of thermodynamics, the input power $\dot{P}$ is:

$$\dot{P} = \dot{Q}_H - \dot{Q}_L = I\alpha(T_W - T_C) + I^2R \tag{9}$$

According to second law,

$$\frac{\dot{Q}_H}{T_W} = S\left(\frac{\dot{Q}_L}{T_C}\right) \qquad with\ S < 1 \tag{10}$$

Substituting equations (7) & (8) into (10), S becomes,

$$S = \frac{\beta(T_W - T_H)T_C}{(T_L - T_C)T_W} \tag{11}$$

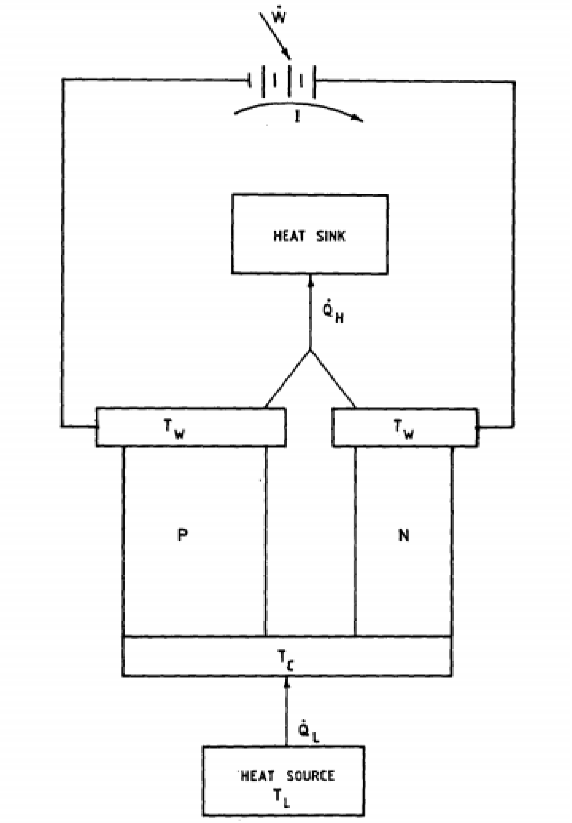


Figure 2 A Thermoelectric Refrigerator

Using equation (9) and dimensionless temperature ratio specified above, the cold junction ratio can be written as:

$$T_C = XT_W \tag{12}$$

Where,

$$X = \frac{S\psi}{S + \beta\left(1 - \frac{\psi}{\tau}\right)} \text{with } \psi < X < 1 \tag{13}$$

Prime requirement of a TER is the optimum refrigeration effect, therefore optimizing $\dot{Q}_L$ with respect to I yields:

$$(I)_{opt} = \frac{\alpha T_W X}{R} \tag{14}$$

$$\phi = \frac{(Q_L)_{opt}}{(\alpha {T_W}^2)/2R} = X^2 + \frac{2(T_H - T_L)}{(Z{T_W}^2)} \tag{15}$$

$$P_{max} = \frac{\dot{W}}{(\alpha T_W)^2/2R} = 2X \tag{16}$$

- For β=0 and *S*=1, *X* approaches to ψ, then equation (15) reduces to the maximum refrigeration effect of TE refrigerator.
- Thermoelectric devices can be characterized by single parameter *X*, named device-design parameter.
- This parameter appears in both the equation for optimum refrigeration effect and maximum input power.
- In order to get high values of *X*, *S* must be decreased for the values of β within the range of interest.
- In order to get better the refrigeration effect, *X* must be increased. [14]

IV. DEVELOPMENT OF TE DEVICES

A. Thermoelectric Cooler

The thermoelectric cooler is a cooling device based on TER principle which has been widely used in military, aerospace, instrument, and industrial or commercial products, as a cooling device for specific purposes. The schematic of the thermoelectric cooler is shown in Figure 3 [13]. Huang et.al. [13] developed a system design method of TE cooler in their study which utilizes the performance curve of the TE module.

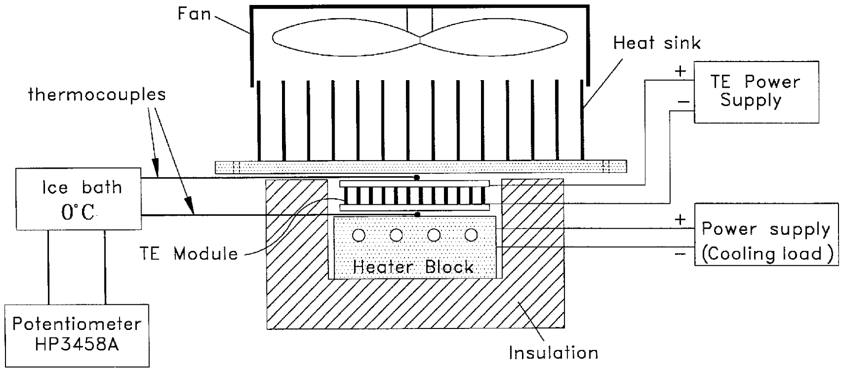


Figure 3 Schematic of Thermoelectric Cooler

Jiajitsawat [15] investigated theoretically & experimentally the effect of combination of TER system & DEAC system. For this he had fabricate a portable hybrid thermoelectric-direct evaporative air cooling system and tested. The schematic of the prototype is shown in Figure 4. [15] The operating principle of the prototype is the conversion of sensible heat of the hot air to the latent heat of water vaporization. Installation of thermoelectric refrigeration system is to remove the sensible heat from the water in the container for further improvement of the air cooling capacity.

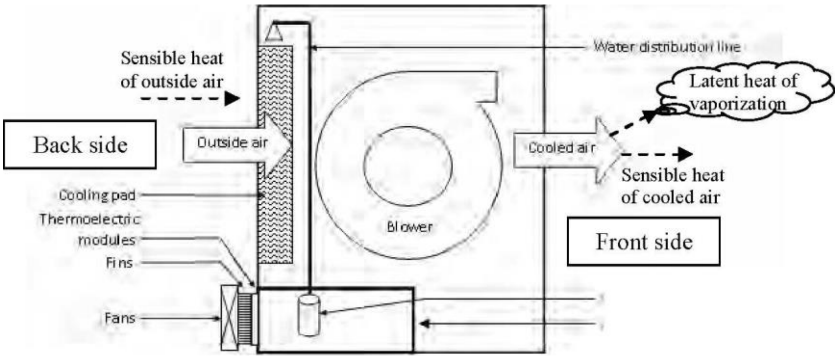


Figure 4 The Combined TE-Direct Evaporative Air Cooler

Experiment was carried out in three ways: Fan operation, Direct evaporative air cooling operation & TER-DEAC operation. When DEAC system is in active, the cooling performance of the prototype increases by 20% & is up to 30% with higher fan speed. The results of TE installation can improve the cooling performance of the DEAC system by 10% and is up to 20% with higher fan speed. Therefore the implementation of TE to DEAC seems to be reliable and possible for commercial application. [15]

B. Thermoelectric Refrigerator

TE modules are also used for constructing thermoelectric refrigerator. Although the COP of a TE module is lower than that of conventional VCR system, efforts have been made to develop thermoelectric domestic refrigerators to exploit the advantages associated with this solid-state energy-conversion technology. The basic configuration of a thermoelectric refrigerator is shown schematically in Figure 5. [16] It consists of a refrigerated cabinet, a Peltier module sandwiched by two heat exchangers, a D.C. power supply and a temperature controller. Although the basic structure of a thermoelectric refrigerator is essentially the same, their configurations may differ significantly depending on the heat exchangers employed. [16]

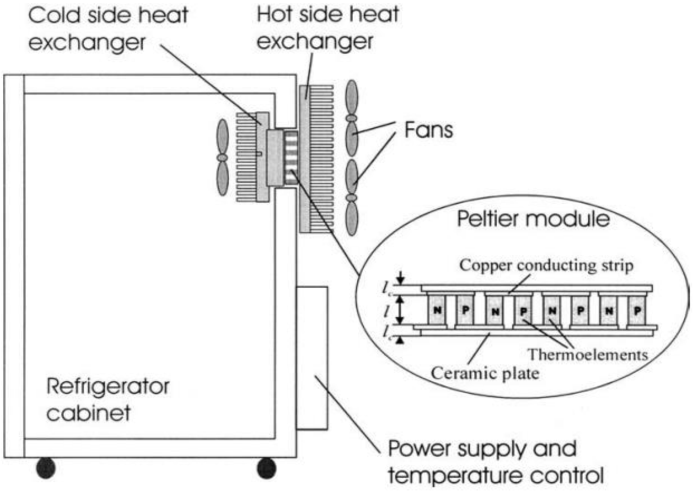


Figure 5 Schematic of Thermoelectric Refrigerator

The thermoelectric refrigeration system is feasible for outdoor purpose in cooperation with solar cells. Dai et.al [17] conducted experimental investigation & performance analysis on prototype of a thermoelectric refrigerator driven by solar cells, which is mainly configured by the array of solar cells, controller, storage battery, rectifier and thermoelectric refrigerator, is shown in Figure 6. [17]

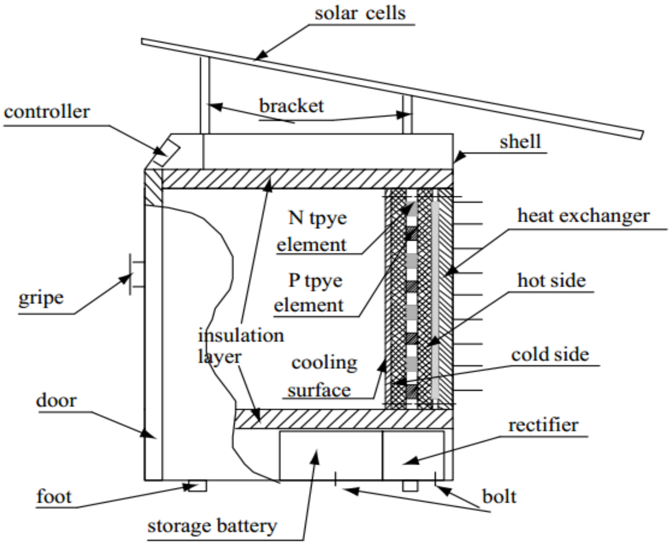


Figure 6 Schematic of Solar Cells driven Thermoelectric Refrigerator

In daytime, solar cells receive solar energy and turn it into electric power supplied to thermoelectric refrigerator by means of photovoltaic effect. If the amount of electric power production is large enough, the power surplus can be accumulated in storage battery besides driving the refrigerator. If the solar cells cannot produce enough electric power, for example, in cloudy or rainy days, the storage battery may offer a makeup. [17]

Experimental results shows that the performance of solar cells driven thermoelectric refrigerator is strongly dependent on the intensity of solar insulation and the temperature difference of hot and cold sides between the thermoelectric module, etc. The studied refrigerator can maintain the temperature in refrigerated space at 5-10^0C, and has a COP about 0.3 under given conditions. [17]

C. Heat exchanger for the cold side of TE module

Vian et.al [18] shows the development of a thermo-siphon with phase change (TSF) which improves the thermal resistance of the heat exchanger of the hot side of the Peltier pellet by 36%, what produces an increase in the COP of a domestic thermoelectric refrigerator of 26% at an ambient temperature of 20^0 C, and 36.5% at 30^0 C. Along this line, Riffat et.al [19] apply the thermo-siphon system, in a thermoelectric heat pump system that works as cooling and heating mode.

The aim is to design and experimentally optimize a heat exchanger which improves the thermal resistance between the cold side of a Peltier pellet and the refrigerated room by the application of the principles of capillarity against gravity, phase change and thermo-siphon. A new device TPM (thermos-siphon porous media) to interchange heat between the cold side of a Peltier pellet and the inner room of a thermoelectric refrigerator has been designed and built. [18]

Figure 7 [18]shows the heat exchanger for the cold side of the TE module.

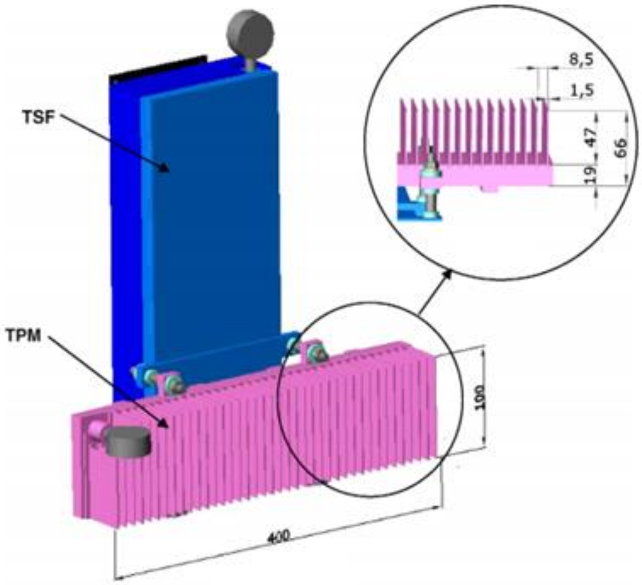


Figure 7 TPM & TSF

V. COP IMPROVEMENT

Due to the fact that TE modules have very low value of COP, many researchers have taken efforts with prime objective of COP improvement. With this objective they have developed TE modules, used different modeling approaches and so on.

A. Optimization of heat dissipation

In this context, D. Astrain et al. [20] developed one device that dissipates heat from hot side of Peltier module. This device works on the principle of thermo-siphon with the phase change. Two thermoelectric domestic refrigerators are used for the experimentation, one of them with the device developed and other with the conventional fins dissipater. It is proved with the help of experiments that the use of thermo-siphon with phase change increases the COP up to 32%. It has been proved in

that for each Celsius degree that we achieve to decrease the temperature drop between the hot side of Peltier and the ambience, we manage to increase the COP of a thermoelectric refrigerator in more than a 2.3%.That is exactly the focus of study: the optimization of heat dissipation from the hot side of the Peltier pellet, in order to increase the COP of the thermoelectric refrigerators. [20]
With the aim of succeeding in spreading uniformly the heat flow through the whole base of the fin dissipater, They have designed a ‘‘TSF’’ device based on thermo-siphon and phase change, which provides a minor thermal resistance and in consequence a minor temperature drop between the hot side of the Peltier pellet and the ambience, which will result in an increase of the COP of the thermoelectric refrigerator. [20]

B. Increment in effectiveness of heat exchangers

The results of the work carried out by Min et al. [21] Showed that an increase in COP of the thermoelectric domestic-refrigerator is possible through improvements in module contact resistances, thermal interfaces and the effectiveness of heat exchangers. A number of prototype thermoelectric refrigerators are investigated and their cooling performances evaluated in terms of the coefficient-of-performance, heat-pumping capacity and cooling-down rate.

Min et al. [21] Studied following 3 prototypes for COP improvement:
TER-1 (Heat exchangers with forced convection)
TER-2 (Forced convection at the cold side and liquid circulation at the hot side)
TER-3 (Liquid circulation heat-exchangers)

This study of the exchangers for the TE module is taken further by again Vian et al [18] by developing HEX for the Cold side of the TE Module. The objective is to design and experimentally optimize a heat exchanger which improves the thermal resistance between the cold side of a Peltier pellet and the refrigerated room by the application of the principles of capillarity against gravity, phase change and thermo-siphon. Their study envelopes the development of a thermo-siphon with phase change (TSF) which improves the thermal resistance of the heat exchanger of the hot side of the Peltier pellet by 36% as elaborated above. During this research they have developed a thermo-siphon with phase change and capillary action (TPM) for the cold side of the Peltier pellet which allows decreasing the thermal resistance and, as a consequence, to improve the COP of thermoelectric refrigerators. [18]

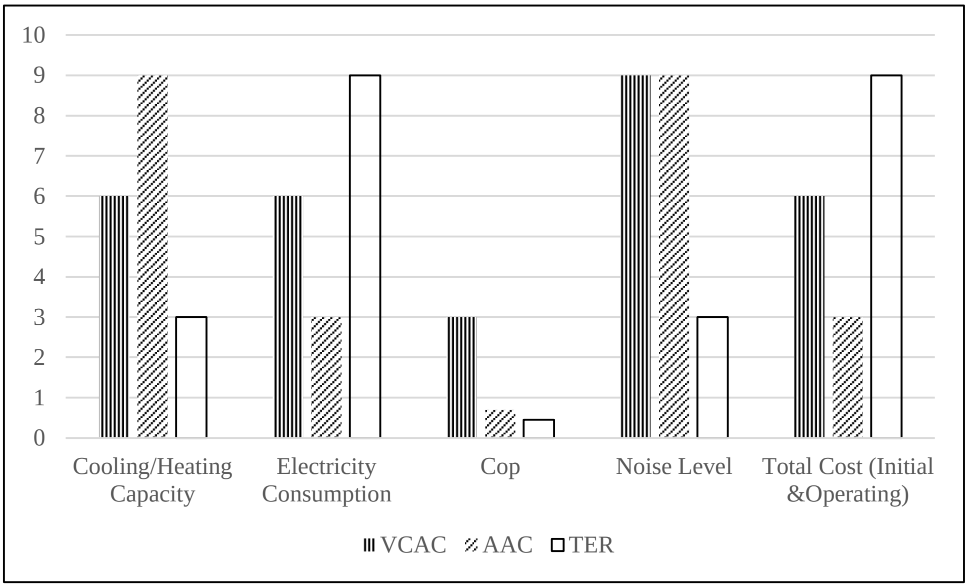
VI. COMPARATIVE ANALYSIS

It is necessary to provide a comparative analysis of thermoelectric refrigeration system at this stage with the other parameters. The aim of this study is to provide an information to the researchers to select appropriate refrigeration system suitable for the application. Hence one should compare TER system on various parameters with the other refrigeration systems.

In a commercial point of view, Riffat et al. [19] Compares TER system with Vapor compression and absorption system, as these two systems are mainly used commercially in the market. This study compares the performance of three types of domestic air conditioning systems and presents methods of COP calculations. The study incudes distinct description of three systems, performance contrast among them, economic analysis and COP analysis & comparison. The conclusions are mentioned parameter wise in Table 1 & Graph 1.

Table 1 Comparison of Three types of Air Conditioners

Parameter	**VCAC**	**AAC**	**TER**
Cooling/Heating Capacity	Medium	High	Less
Electricity Consumption	Medium	Low	High
Cop	2.6-3.0	0.6-0.7	0.38-0.45
Noise Level	Noisy	Noisy	Quiet
Total Cost (Initial &Operating)	Medium	Lowest	Highest



Graph 1 Comparison of Three types of Air Conditioners

A. Effect of number of stages

The simplest mode of thermoelectric refrigeration is to use a single-stage thermoelectric device. However, due to the performance limits of thermoelectric materials, a single-stage thermoelectric refrigerator can only be operated over a small temperature range. If the temperature ratio between the heat sink and the cooled space is large, a single-stage thermoelectric refrigerator will lose its effectiveness. Thus, the application of two- or multi-stage combined thermoelectric refrigerators is an important method of improving the performance of thermoelectric refrigerators.

Chen et al. [22] Compared the performance of single stage and two stage thermoelectric refrigeration system. For this they established cycle model of single and two stage TER system and derived general expressions of three important performance parameters such as COP, Rate of refrigeration and power input.

It states maximum COP of two stage is larger than that of single stage but maximum rate of refrigeration is smaller. In general, it is more convenient to use directly a single-stage thermoelectric refrigeration system when the temperature ratio of the heat sink to the cooled space is small. However, when the temperature ratio of the heat sink to the cooled space is larger, both the maximum COP and the maximum rate of refrigeration of a two-stage thermoelectric refrigeration system are larger than those of a single-stage thermoelectric refrigeration system. The study of Chen et al. [22] Provides some theoretical bases for the optimal design and operation of a two-stage thermoelectric refrigeration system. [22]

Karimi et al. [23] Analyzed and fabricated a new device with multistage or stack of single stage TE module. Multi-stage thermoelectric coolers offer larger temperature differences between heat source and heat sink than single or two stage thermoelectric coolers. In this study, a pyramid type multi-stage cooler is analyzed, focusing on the importance of maximum attainable target heat flux and overall COP. Having considered the COP and the thermal resistance of a heat sink as key parameters in the design of a multi-stage thermoelectric cooler, analytical formulas for COP and heat sink thermal resistance versus working electrical current are derived. The study concludes that multistage TER system allows use of heat sink with higher thermal resistance which helps in improvement of COP. [23]

VII. CONCLUSION

This paper reviews the developments in TER system over the years. This study on the thermoelectric refrigeration emphasize that the TER system is a novel refrigeration system which will be a better alternative for conventional refrigeration system. The research and development work carried out by different researchers on TER system has been thoroughly reviewed in this paper. The study of this seminar spreads over the application of TER system and various technologies used with the same. This seminar summarizes the advancement in thermoelectric refrigeration, thermoelectric materials, recent modeling approaches, application in domestic appliances and various technologies.

This paper also concludes that, to achieve better COP & temperature control we can combine TER with other refrigeration systems. For example combining VCR & TER systems reduces the energy consumption, gives high COP & good temperature control within the refrigerated area. Hence it is better to have such hybrid systems & devices to reduce total energy consumption.

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