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# Thermoelectric Cooling

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## Abstract

In this chapter, design and analysis study of thermoelectric cooling systems are described. Thermoelectric (TE) cooling technology has many advantages over the conventional vapor-compression cooling systems. These include: they are more compacted devices with less maintenance necessities, have lower levels of vibration and noise, and have a more precise control over the temperature. These advantages have encouraged the development of new applications in the market. It is likely to use TE modules for cooling the indoor air and hence compete with conventional air-conditioning systems. These systems can include both cooling and heating of the conditioned space. In order to improve the performance of the TE cooling systems, the hot side of the TE should be directly connected to efficient heat exchangers for dissipation of the excessive heat. Finally, TE cooling systems can be supplied directly by photovoltaic to produce the required power to run these cooling systems.

**Keywords:** thermoelectric coolers, heat transfer, heat exchangers, thermal modeling, cooling performance, solar power

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## 1. Introduction

There are three main types of cooling systems used in air conditioners and refrigerators; each has its own advantages and disadvantages [1]. Air conditioners, however, have better performance than refrigerators as only a smaller temperature difference than refrigerators is required [1]. Vapor compression coolers have a high coefficient of performance (COP) and high cooling capacities. However, they have a noisy operation and use refrigerants with high global warming potential (GWP) such as R134a. R513A is a lower GWP alternative of R134a; however, it generally reduces the COP of the cooling systems [2]. Absorption coolers have moderate values of COP with the advantage of recovering waste heat. However, such systems are usually heavy and bulky. Thermoelectric (TE) coolers are portable with no noise, but they have

relatively low COPs. Various studies on thermoelectricity have examined its operation with power directly supplied by photovoltaic to produce the required electricity to run the cooling systems [3, 4]. The electrical current supplied by photovoltaic which is consumed by TE devices, is a direct current so that no DC/AC inverter is required.

Using TE modules, several researchers reported cooling small volumes such as submarines [5]. TE modules have been proposed to be used in building applications using active building envelopes [6, 7]. Such studies underlined the promising future of the TE modules in cooling applications.

General comparison between these three types of coolers for air conditioners is shown in **Table 1** [8].

Recent studies provide two possible directions that can lead to considerable progress in TE cooling [3]:

1. improving intrinsic efficiencies of TE materials, and
2. improving thermal design and optimization of the current available TE cooling modules.

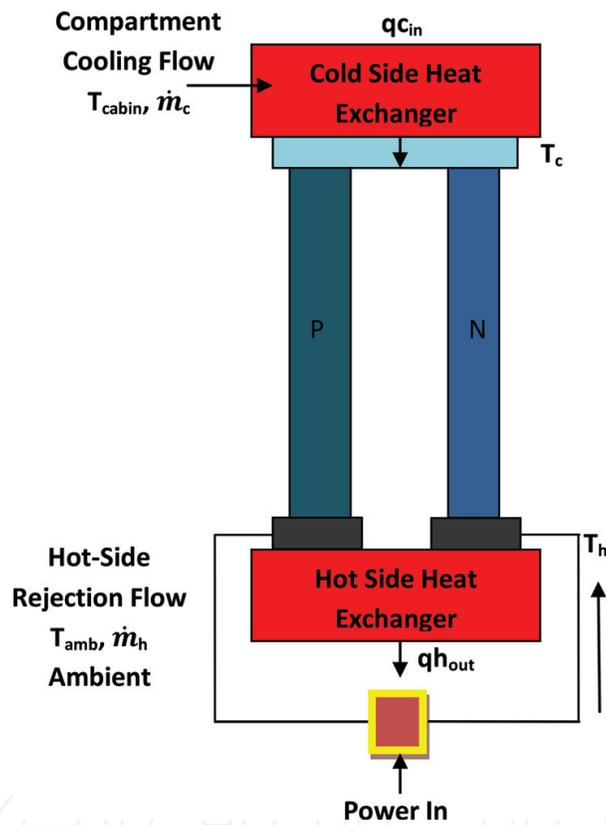
Introducing efficient heat sinks at both the hot and cold side of TE coolers greatly influences the cooling COP. Air cooled heat sink forced convection with fan [9, 10], water cooled heat sink [11] and heat sink integrated with heat pipe [12, 13] are frequently employed techniques. This review will focus on the development of TE cooling with great concerns on advances in materials, modeling and optimization approaches.

Type	VCAC	AAC (single effect)	TEAC
Cooling			
Cooling capacity, W	2500–4500	15–2x104 KW	15–560
Input electric power, W	750–1670	1.8–54 KW	36–1495
COP <sub>c</sub>	2.6–3.0	0.6–0.7	0.38–0.45
Work permit temperature range, °C	18–45	N/A	0–70
Noise, Db	35–48 Indoor	N/A	N/A
Size	Medium	Big	Small
Life expectancy, years	10–12	≈ 15	≈ 23
Price	Low	High	High

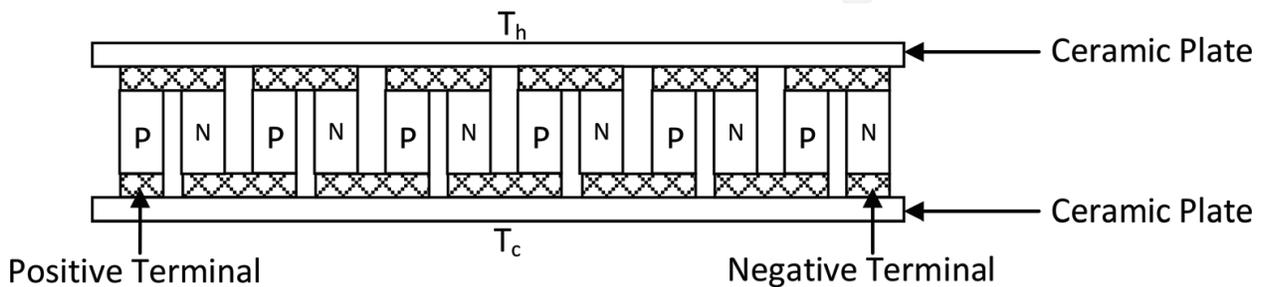
**Table 1.** Comparison between the three types of coolers for air conditioners.

## 2. Thermoelectric coolers

When two different metals or semiconductors are connected together and the two connections held at different temperatures, there are many irreversible phenomena that can take place at the same time [14]. These are the Joule effect, Fourier effect, Thomson effect, Seebeck effect and Peltier effect. The Peltier effect is the most interesting among them for TE cooling. If a circuit contains two connections between different conductors or semiconductors, applying a DC volt will cause heat to transfer from one junction to the other. For producing the Peltier effect, semiconductor alloy materials, such as  $\text{Bi}_2\text{Te}_3$  and SiGe, are better than metals [15]. The principle of TE coolers utilizing semiconductor Peltier effects is shown in **Figure 1**. The heat is



**Figure 1.** Principle of thermoelectric coolers utilizing semiconductor Peltier effects.



**Figure 2.** A conventional thermoelectric module with multiple thermoelements.

transferred from the cooled space to the hot-side heat sink through n-type and p-type semiconductor thermoelements which rejects the heat to the environment. The heat flow direction through the semiconductor materials will be reversed if the electric current direction is reversed.

A typical TE module usually consists of a large number of n-type and p-type bulk semiconductor thermoelements that are connected electrically in series and thermally in parallel and sandwiched between two ceramic plates, as illustrated in **Figure 2**.

### 3. Applications using thermoelectric coolers

Commercially available TE coolers are used in applications where design criteria of the cooling system include factors such as high reliability, low weight, small size, intrinsic safety for hazardous electrical environments and accurate temperature control. TE coolers are more appropriate for unique applications such as space missions, medical and scientific equipment where low COP is not an apparent disadvantage.

TE cooling devices are used for cooling small volumes, such as portable and domestic refrigerator, portable icebox and beverage can cooler [12, 16–21], where the cooling requirements are not too high. In general, the COP for both domestic and portable thermoelectric refrigerators is usually less than 0.5, when operating at an inside/outside temperature difference between 20 and 25°C.

Electronic devices like PC processors produce very large amount of heat during their operation which add great challenge to the thermal management as reliable operation temperature for these electronic devices has to be maintained. TE cooling devices have also been applied to scientific and laboratory equipment cooling for laser diodes and integrated circuit chips [22] to reduce the thermal noise and the leakage current of the electronic components where conventional passive cooling technologies cannot fully meet the heat dissipation requirements. For example, cooling CdZnTe detectors for X-ray astronomy between 30 and 40°C can reduce the leakage current of the detectors and allows the use of pulsed reset preamplifiers and long pulse shaping times, which significantly improves their energy resolution. Integrating thin film TE coolers with microelectronic circuits has been implemented using micromachining technology.

TE cooler appears to be especially favorable for automotive applications [23]. Besides the automobile air-conditioning system and automobile mini refrigerators, researchers also utilized TE device to control car seat temperature to either cooling down or heating up [24].

Some researchers are trying to improve thermoelectric domestic air-conditioning systems [25–27] hoping that these systems can be competitive with the current widely used vapor compression systems. They investigated TE cooling devices for small-scale space's conditioning application in buildings [26]. A TE cooling unit was assembled and generated up to 220 W of cooling capacity with a maximum COP of 0.46 under the input electrical current of 4.8 A for each module.

Active thermal window (ATW) and transparent active thermoelectric wall (PTA) were also introduced for room cooling application in applications where conventional air-conditioning

system is not easy to install [28, 29]. Thermoelectric cooling has also been applied in other occasions, such as generating fresh water [30–33] and active building envelope system [7, 34].

TE systems can be directly connected to a PV panel. Since TE devices are low voltage driven devices, they can accept a power supplied by PV panel without conversion. This advantage makes TE devices attractive for building air-conditioning applications [27, 30]. This solar cooling technique can reduce the energy consumption and the environmental impact issues raised by conventional refrigeration and air-conditioning systems. Batteries can also be used to store DC voltages when sunlight is available while supplying DC electrical energy in a discharging mode in the absence of daylight. A battery charge regulator is needed to protect the battery from overcharging. Solar thermoelectric can be used in cooled ceiling applications to remove of a large fraction of sensible cooling load. In this case, the TE modules are connected in series and sandwiched between aluminum radiant panels and heat pipe sinks in ceilings [35].

#### 4. Analysis of thermoelectric elements

The basic unit of the TE cooler is the n-type and p-type thermoelements. A bottom-up modeling approach is to construct the model at element level with the assumption that both types of thermoelements are exactly the same but opposite direction of the Peltier-Seebeck effect.

In the cooling mode, the cooling capacity  $Q_c = (mc_p)_c (T_{c\text{out}} - T_{c\text{in}})$ , the heat dissipated in the hot-side heat sink  $Q_h = (mc_p)_h (T_{h\text{out}} - T_{h\text{in}})$ , the electric input power  $W = Q_h - Q_c$ , and the cooling COP<sub>c</sub> can be expressed by:

$$\text{COP}_c = \frac{Q_c}{W} = \frac{1}{\frac{T_{h\text{out}} - T_{h\text{in}}}{T_{c\text{out}} - T_{c\text{in}}} C_r - 1} \quad (1)$$

where  $T_{c\text{in}}$  is the temperature of the inlet fluid in the cold side of the TE system,  $T_{c\text{out}}$  is the temperature of the outlet fluid in the cold side of the TE system,  $T_{h\text{in}}$  is the temperature of the inlet fluid in the hot side of the TE system,  $T_{h\text{out}}$  is the temperature of the outlet fluid in the hot side of the TE system,  $(mc_p)_c$  is the thermal conductance of cold side of the TE system,  $(mc_p)_h$  is the thermal conductance of hot side of the TE system,  $m$  is the mass rate of the fluid,  $c_p$  is the specific heat capacity of the fluid and  $C_r = \frac{(mc_p)_h}{(mc_p)_c}$  is the heat capacity ratio. In the heating mode,  $\text{COP}_h = \frac{Q_h}{W} = 1 + \text{COP}_c$ .

If some of the parameters for TE elements are available, the ideal COP<sub>c</sub> (COP<sub>C,id</sub>) and COP<sub>h</sub> (COP<sub>h,id</sub>) can be expressed as:

$$\text{COP}_{C,\text{id}} = \frac{Q_c}{W} = \frac{\alpha_{pn} T_c - \frac{KR\Delta T}{V} - \frac{1}{2}V}{V + \alpha_{pn}\Delta T} \quad (2)$$

$$\text{COP}_{h,\text{id}} = \frac{Q_h}{W} = \frac{\alpha_{pn} T_h - \frac{KR\Delta T}{V} + \frac{1}{2}V}{V + \alpha_{pn}\Delta T} \quad (3)$$

where  $\alpha_{pn}$  is the Seebeck coefficient,  $R$  is the electrical resistivity,  $K$  is the thermal conductivity,  $V$  is electrical applied volt and  $\Delta T = T_h - T_c$  is the temperature difference between the cold and the hot side of thermoelements at the ceramic plate locations.

For the optimum working voltage  $V_{opt}$  and optimum working current  $I_{opt}$ ,

$$V_{opt} = \frac{\alpha_{pn} \Delta T}{\sqrt{1 + ZT_m} - 1} \quad (4)$$

$$I_{opt} = \frac{V_{opt}}{R} = \frac{\alpha_{pn} \Delta T / R}{\sqrt{1 + ZT_m} - 1} \quad (5)$$

The corresponding maximum  $COP_{c,d}$  i.e.,  $COP_{c,opt}$  will be;

$$COP_{c,opt} = \frac{T_c}{T_h - T_c} \frac{\left(\sqrt{1 + ZT_m} - \frac{T_h}{T_c}\right)}{\left(\sqrt{1 + ZT_m} + 1\right)} \quad (6)$$

where  $T_m$  is the average temperature of the thermocouple defined as:

$$T_m = \frac{1}{2}(T_h + T_c) \quad (7)$$

Similarly, the optimum coefficient of performance of heating  $COP_{h,opt}$  can be expressed as:

$$COP_{h,opt} = \frac{T_h}{T_h - T_c} \left(1 - 2 \frac{\sqrt{1 + ZT_m} - 1}{ZT_m}\right) \quad (8)$$

A comprehensive parameter that described the thermoelectric characteristics is the figure of merit of the thermocouple  $Z$  which can be defined as:

$$Z = \frac{(\alpha_p - \alpha_n)^2}{(KR)_{min}} = \frac{\alpha_{pn}^2}{(KR)_{min}} \quad (9)$$

This parameter can be made dimensionless by multiplying it by  $T$  (the average temperature of the hot side and the cold side of the TE module):

$$ZT = \frac{\alpha_{pn}^2 T}{(KR)_{min}} \quad (10)$$

The value of  $Z$  is related only to the physical properties of the thermocouple material. The higher the figure of merit  $Z$  for the material, the better the thermoelectric properties it has. The best commercial thermoelectric materials currently have  $ZT$  values around 1.0. The highest  $ZT$  value reported in research is about 3 at temperature of 550 K [36].

Maximizing  $Q_c$  and COP can be obtained by optimizing some parameters like the number of thermoelement pairs for each stage and the applied electrical current [37]. For cascaded

coolers, the expression for the cooling rate  $q_i$  per unit area for the  $i^{\text{th}}$  stage, depending on the COP of the  $i^{\text{th}}$  stage and on the cooling rate per unit area of the  $i^{\text{th}}$  stage  $q_1$  in connection with the heat source, can be presented by [38]:

$$q_i = q_1(1 + COP_1^{-1})(1 + COP_{I-1}^{-1})\dots(1 + COP_{I-i}^{-1}) \quad (11)$$

In this context, each stage, that is considered from the heat source to the heat sink, must have a cooling capacity higher than the one in the previous stage. Truly, each stage will reject both the extracted heat from the previous stage and the electrical power supplied to the stage. Theoretical study for internally cascaded multistage TE couples showed that an enhancement of a 25.2% in the maximum COP can be achieved by using cascaded 3-stage TE modules [39]. A 1400 W TE air-conditioning system using multiple TE modules was investigated [40].

## 5. Development of thermoelectric materials

As shown by the primary criterion of merit, a good thermoelectric material should possess high Seebeck coefficient, low thermal conductivity and high electrical conductivity. However, these three parameters are interrelated; hence they have to be optimized to get the maximized  $ZT$  [41, 42]. The changes in these parameters will unlikely lead to a net increase in  $ZT$ , since any favorable change in one parameter will be accompanied by an unfavorable change in the other parameters. For instance, if the electrical conductivity is too low, we might like to increase the carrier concentration. However, during increasing the carrier concentration which in turn will increase the electrical conductivity, the Seebeck coefficient will also decrease and the electronic contribution to the thermal conductivity will increase. This dilemma forced the maximum  $ZT$  of any thermoelectric material to be held at  $ZT = 1$  for many years [43]. The devices made of these materials were operated at a power conversion efficiency of only 4–5%.

Conventional thermoelectric materials are bulk alloy materials such as  $\text{Bi}_2\text{Te}_3$ ,  $\text{PbTe}$ ,  $\text{SiGe}$  and  $\text{CoSb}_3$ . Eventually it was determined that the most efficient bulk thermoelectric materials are high carrier concentration alloyed semiconductors. The high carrier concentration results in a good electrical conductivity while optimizing the electrical properties can be achieved by varying the carrier concentration. Transport of phonons (quantized lattice vibrations which carry heat) can be disrupted by alloying, which results in a reduced thermal conductivity. For this approach, it was discovered that good thermoelectric materials are phonon-glass electron-crystal material [44, 45], where high mobility electrons are free to transport charge and heat but the phonons are disrupted at the atomic scale from transporting heat. The recent trend to optimize the thermoelectric material's performance is achieved by reducing the material thermal conductivity, especially the lattice thermal conductivity [46]. Reducing the lattice thermal conductivity can be achieved by adding low sound velocity heavy elements, such as Bi, Te, and Pb. Examples of commercial thermoelectric alloys include  $\text{Bi}_x\text{Sb}_{2-x}\text{Te}_3$  at room temperature,  $\text{PbTe-PbSe}$  at moderate temperature, and  $\text{Si}_{80}\text{Ge}_{20}$  at high temperature.

A new strategy for high efficiency “phonon-liquid electron-crystal” thermoelectric materials where a crystalline sublattice for electronic conduction is surrounded by liquid like ions was

introduced. The results of an experiment performed on a liquid like behavior of copper ions around a crystalline sublattice of Se in  $\text{Cu}_{2-x}\text{Se}$  showed a very low lattice thermal conductivity which increased the value of  $ZT$  in this simple semiconductor [47].

The efficiency of TE devices can be further enhanced through nanostructural engineering [44] using two primary approaches: bulk materials containing nano-scale constituents and nano-scale materials themselves. By the introduction of nanostructures,  $ZT$  was pushed to about 1.7 [48] with power conversion efficiency of 11–15%.

Many reviews have summed up progress on thermoelectric materials [49, 50], bulk thermoelectric materials [45] and low-dimensional thermoelectric materials [43, 51, 52]. Low-dimensional materials, including 2-D quantum wells, 1-D quantum wires and 0-D quantum dots, possess the quantum confinement effect of the electron charge carriers that would enhance the Seebeck coefficient and thus the power factor [53]. Furthermore, the introduced various interfaces will scatter phonons more effectively than electrons so that it reduces the thermal conductivity more than the electrical conductivity [18].

Two-dimensional  $\text{Bi}_2\text{Te}_3$  quantum well improved  $ZT$  due to the enhancement of thermopower [54]. The  $ZT$  of  $\text{Bi}_2\text{Te}_3$  quantum well structures are estimated to be much higher than its bulk material. The highest  $ZT$  observed was 2.4 using  $\text{Bi}_2\text{Te}_3\text{-Sb}_2\text{Te}_3$  quantum well superlattices with a periodicity of 6 nm [55]. Similarly, the highest  $ZT$  value for its bulk material is only 1.1. Quantum-dot superlattices in the  $\text{PbTe-PbSeTe}$  system were developed under the quantum confinement may lead to an increased Seebeck coefficient and therefore higher  $ZT$  [56].  $\text{PbSe}$  nanodots were embedded in a  $\text{PbTe}$  matrix and showed  $ZT$  of 1.6, which is much higher than their bulk materials of 0.34 [52]. Serial compound  $\text{Ag}_{1-x}\text{Pb}_{18}\text{SbTe}_{20}$  has a high  $ZT$  value of 2.2 at 800 K due to the special nanostructure that is still the most competitive TE material [57] and has ignited broad research interest [58–61]. These new technologies have pushed  $ZT$  to 2.4 [62] with predicted increase in the device conversion efficiency to a value between 15 and 20%.

## 6. Modeling approaches for thermoelectric cooling

Both system cooling power output and cooling COP should be considered for enhancing TE cooling system performance. There are three methods that can possibly lead to this enhancement. First, TE module design and optimization, such as number of thermocouples [63–66], thermoelement length [67–70] and thermoelement length to cross-sectional area ratio [71–73]. Second, cooling system thermal design and optimization [74], which includes investigation of heat sinks' geometry [75–77], identification of the heat transfer area and heat transfer coefficients of both hot and cold side heat sinks [78–80], more effective heat sinks (i.e. heat sink integrated with thermosyphon and phase change material) [16, 81, 82], thermal and electrical contact resistances and interface layer analysis [83–85]. Third, the TE cooling system working conditions (i.e. electric current input [86–88]), heat sink coolant and coolant's mass flow rate [10, 89].

In order to achieve this, a variety of system optimization methods have been adopted. The simplified energy equilibrium model for TE cooler can satisfy many different TE cooling

applications including electronic devices cooling and air conditioning [90–94]. If the TE modules are employed with time-varying temperature distribution and cooling power output, either 1D or 3D transient modeling is needed to better capture the system performance. To capture the module performance, modeling temperature change in all thermoelements is very complicated. Therefore, energy equilibrium model can be applied to simplify the numerical analysis process, especially for those systems which include heat sinks in hot and cold sides.

Positive Thomson coefficient improves TE cooling performance by 5–7% [95], while negative Thomson coefficient reduces cooling performance [96]. However, for commercially available TE coolers, Thomson effect is often small and negligible. Dimensionless analysis is a powerful tool to evaluate the performance of TE cooling system. New dimensionless parameters, such as dimensionless entropy generation number [78], dimensionless thermal conductance ratio and dimensionless convection ratio [64] have been defined.

Both COP and cooling capacity are dependent on the length of thermoelement, and this dependence becomes highly significant with the decrease in the length of thermoelement [97]. As a result, a long thermoelement is preferred to obtain a large COP, while a short thermoelement would be preferable to achieve maximum heat pumping capacity. Therefore, it is obvious that the design of the optimum module will be a tradeoff between the requirements for the COP and the heat pumping capacity. Most commercially available TE modules have thermoelement length range from 1.0 to 2.5 mm. Cooling power density also increases with decreasing the ratio of thermoelement length to the cross-sectional area.

Typical TE modules have a size range from  $4 \times 4 \times 3 \text{ mm}^3$  to about  $50 \times 50 \times 50 \text{ mm}^3$ . The development of micro-TE devices to further reduce the dimensions, that is compatible with standard microelectronic fabrication technology [98], has the potential to improve the micro-electronic systems performance, achieve considerable reductions in size and improve the TE devices performance, which opens up new commercial applications.

Electrical and thermal contact resistances, especially thermal contact resistance at the thermoelement interface layer, are critical to achieve a further improvement in both TE cooling capacity and COP [84]. An enhanced formula for the COP of a Peltier module which takes into consideration both the electrical and the thermal contact resistances can be written as [34]:

$$\text{COP}_{opt} = \frac{l}{l + 2rl_c} \left( \frac{T_c}{T_h - T_c} \frac{\beta - T_h/T_c}{1 + \beta} - \frac{rl_c}{l} \right) \quad (12)$$

where

$\beta = \left( 1 + \frac{lZT_M}{n+l} \right)^{1/2}$ ,  $n = \frac{2R_c}{R}$ ,  $r = \frac{k}{k_c}$ ,  $l$  is the thermoelement length,  $l_c$  is the thickness of the contact layer,  $k$  is the thermal conductivity of the thermoelements,  $k_c$  is the thermal conductivity of the contact layers and  $T_M = \frac{(T_h + T_c)}{2}$ .

In addition, an accurate fabrication technique is needed to provide high-quality and high-performance TE modules. The requirements include: precise measurements of the internal resistance for each module at ambient temperature; determination of the module supply leads

resistance; consideration of optimum values for voltage and current of each module; verification of thermal efficiency of each module and calculations of temperature difference, maximum cooling capacity according to the measurement results, figure of merit and values of internal resistance [99].

Heat sink performance at the hot side is more important than heat sink at the cold side because the heat flux density at hot side is higher. Allocation of the heat transfer area or heat transfer coefficients between hot and cold sides is particularly important. For given hot and cold side fluid temperatures, there exists an optimum cooling capacity which leads to maximum COP [64, 80, 92].

The COP of TE devices could be improved by minimizing the difference in temperature between their hot and cold faces [100]. The hot side of the TE cooler exhibits very high power densities that demands sophisticated cooling infrastructure with high pumping power.

## 7. Heat transfer analysis of the heat exchanger

To enhance the heat transfer rate between the hot and the cold fluid flows, heat exchangers are commonly applied in air cooling systems. Relations between the hot and the cold side temperatures as well as the optimum heat transfer surface area can be calculated by applying energy balances to both the hot and the cold sides of the TE modules over a differential area [101].

The heat transfer on the hot side of the TE devices can be increased using cross air flow or counter air flow [102]. The COP of TE devices could be improved by minimizing the difference in temperature between their hot and cold faces while applying appropriate electrical power [100]. A TE system used for cooling or warming airflow with a high COP of 1.5 was reported [93]. To achieve such a relatively high COP, the temperature difference between the hot and the cold faces of the TE modules was maintained at 5°C.

Other favorable working strategies using different heat transfer methods such as liquid cooling with phase change materials were also reported [103]. Theoretical and experimental studies were conducted to examine the performance characteristics of TE water cooling system for electronic cooling applications under small heat loads [11]. A TE liquid chiller was developed with 430 ml capacity and a COP ranged between 0.2 and 0.8 for a temperature of 5–15°C below ambient [104]. A cylindrical, water-cooled heat sink for TE air conditioners was designed and characterized [105]. In this context, a thermosyphon with phase change was developed to improve the thermal resistance of the heat exchanger at the hot side of the TE by 36% [12]. This increased the COP of a TE module by 26% at an ambient temperature of 20°C and 36.5% at 30°C. Using evaporative cooling the COP of TE air-conditioning system was improved by 20.9% [106].

TE devices, as electronic components, do not allow direct contact with coolant. Therefore, instead of pumping coolant directly through TE coolers, channels plate liquid cooling system is used. A channels plate block is a heat conductive metal, such as aluminum or copper, which is filled with channels. The base of the water block is a flat metal surface that is placed directly on top of the hot side of the TE module being cooled using thermal paste to improve

transferring the heat between the two surfaces. When the TE hot side heats the block, the liquid coolant absorbs the heat as it flows through all the channels, which will be dissipated through a radiator. The same system can be applied at the cold side for the transfer of the cool due to high thermal resistance between the cold side of the TE and the space being cooled.

Recently, heat transfer in mini channels within heat exchangers is drawing substantial attention trying to improve their performance. The proper selection of channel dimensions and nonuniform distribution of the channels can improve the cooling power [107]. Therefore, thermal and hydrodynamic characteristics of channels need to be examined and developed. A TE system using liquid cooling for electronic application using micro-channel heat sink was proposed and its experimental analysis performance was investigated [108]. The effect of channel width, coolant flow rate and heat sink material on the heat transfer rate was also examined [76].

Although micro-channel heat exchangers are able to dissipate higher heat flux densities, the slow flow rate creates a large increase in the temperature alongside the direction of the coolant flow in both channel material and the coolant. Surface roughness also participates in the heat transfer characteristics and the drop of pressure of coolant flow in a channel. Many studies clearly reported that the roughness has an effect on the flow of the coolant and heat transfer characteristics, in addition to the laminar and turbulent transition [109, 110]. Micro channel heat exchangers with different designs and coolants were manufactured and tested and the experimental results confirmed the superiority of this cooling technique [111, 112].

Heat removal through parallel channels involves a complex combination of convection, conduction and coolant flow. In a rectangular channel plate with width  $W$ , height  $H$  and length  $L$ , taking the advantage of the symmetry of the channels, a unit cell containing only one channel with the surrounding metal is chosen. The results obtained can easily be applied to the whole plate. Heat transport in the unit cell is a conjugate problem that mixes heat conduction in the metal and convective heat transfer to the coolant. The dissipated heat in the surrounding regions conducts to the channel side walls, which is then absorbed, through convection, by the coolant and carried away by the circulation.

These parameters can be summarized by stating them as thermal resistances. Conductive resistance,  $R_{cond}$  is determined by thermal characteristics of aluminum that conducts the dissipated heat in the region surrounding the sidewalls of the channel. Convection resistance,  $R_{conv}$  is a result of the convection from sidewalls of the channel to the coolant. Heat resistance,  $R_{heatr}$  is a result of heating up of coolant in the downstream direction as the flow is pushed toward the channel exits. These can be expressed as:

$$R_{conv} = \frac{1}{h A} \quad (13)$$

where  $A$  is the channel surface area. Assuming that heat is transmitted from all the sidewalls, the surface area will be:

$$A = 2 L(W + H) \quad (14)$$

here  $h$  is the convective heat transfer coefficient:

$$h = \frac{N_u K_f}{D_h} \quad (15)$$

where  $K_f$  is coolant thermal conductivity,  $N_u$  is the Nusselt number calculated with the Dittus-Boelter equation [113],

$$N_u = 0.023 P_r^{0.4} R_e^{0.8} \quad (16)$$

in which  $P_r$  is Prandtl number and  $R_e$  is Reynolds number.  $D_h$ , the hydraulic diameter, is defined as:

$$D_h = \frac{4 (\text{cross sectional area})}{\text{perimeter}} = \frac{4 WH}{2 (W + H)} \quad (17)$$

Hence the convective can be expressed as:

$$R_{conv} = \frac{D_h}{2 N_u K_f L (W + H)} \quad (18)$$

The heat resistances can be expressed as:

$$R_{heat} = \frac{1}{C_p \rho_c f} \quad (19)$$

where  $C_p$  is the coolant specific heat and  $\rho_c$  is coolant density.  $f$  is the volumetric flow rate for each channel which is defined as:

$$f = \text{coolant velocity}^* \text{ cross sectional area} = v W H \quad (20)$$

The coolant viscosity and thermal conductivity vary according to the temperature [114]. The conductive resistances can be expressed as:

$$R_{cond} = \frac{W}{k L H} \quad (21)$$

where  $k$  is the thermal conductivity of the channels plates material.

For fluid dynamical and thermal phenomena that occur in the channels with corrugated walls, different heat transfer characteristics can be observed. Generally, the wall corrugation enlarges the surface of the channels and creates turbulence. However, most studies stated that the rise in temperature of the walls along the direction of the flow is almost linear [115–117].

Recently, heat sinks with nano-fluid have shown potential to achieve lower thermal resistance [118, 119]. In addition, cooling technologies based on heat removal from the heat sinks using synthetic jet [120], either single-phase or two-phase flow, are noticeable.

## 8. Conclusions

In this chapter, a short review of technologies related to the TE cooling was presented. The new methodologies of system design and system analysis have enabled the design of high-performance TE cooling systems. This includes the use of the basic physical properties of TE modules and the flow equations to identify the TE cooling design parameters to maximize the COP of the TE cooling systems. To minimize the energy demands in TE cooling systems and increase their energy effectiveness, solar TE cooling technologies such as active building envelope, solar thermoelectric coolers are suggested to be used in zero-energy environments.

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