academicJournals

Vol. 8(12), pp. 485-492, 4 April, 2013
DOI 10.5897/SREX12. 001
ISSN 1992-2248 © 2013 Academic Journals
http://www.academicjournals.org/SRE

Scientific Research and Essays

Review

A review on thermoelectric cooling modules: Installation design, performance and efficiency

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Accepted 4 April, 2013

A thermoelectric cooling module (TECM) is defined as a solid-state heat pump and present advantages (for example, no moving parts and no harmful gasses) over other refrigeration technologies. However, to optimally use TECMs as high efficient heat pumps it is crucial to understand the factors that influence the performance and efficiency of these modules during the installation design phase. This paper therefore provides a review on the installation design phase of TECMs together with the factors that influence the performance and efficiency during this phase. Information and a discussion on the hot and cold surface calculations, power supply calculations and heat sink calculations are provided in this work. The performance of the TECMs is influenced by the Joule heating effect, temperature difference over the TECMs and thermal conductance between the p-n junctions. The efficiency of the TECMs is influenced by the coefficient of performance (COP) and the method and type of control of the TECMs. These factors are discussed in detail. It is shown that the factors related to the performance and efficiency of the TECMs cannot be disregarded and must be taken into account during the installation design phase of the TECMs.

Key words: Thermoelectric cooling modules, installation design, performance, efficiency.

INTRODUCTION

This paper provides a review on the installation design of thermoelectric cooling modules (TECM) to operate as high efficient heat pumps and the factors that influence the performance and efficiency of the TECMs during the installation design phase. When DC power is applied to the TECM, heat is moved from the cold surface to the hot surface. The direction in which the heat is pumped is directly related to the direction of the current. When the direction of the current is reversed, the direction in which the heat is pumped is also reversed. This phenomenon is known as the Peltier Effect and it is the inverse of the Seebeck Effect (Rogers and Mayhew, 1991).

The theory, on which the thermoelectric module is based on, existed from 1911 (Tritt, 2002). In this time, there were no suitable materials to ensure that the modules cooled effectively. The metals that were used allowed for a low coefficient of performance (COP) of 1% (Tritt, 2002). This is because metals have a good thermal conductivity and conduct the heat from the hot surface of the module to its cold surface. Semiconductor materials were discovered in 1950, which lead to the improvement in the COP. The semiconductors have a much lower thermal conductivity than metals so that the COP is improved up to 20% (Slack, 1995). The elements that semiconductors are made of is bismuth (Bi), cadmium (Cd), antimony (Sb), tellurium (Te), selenium (Se)

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and zinc (Zn). Bismuth tellurid (Bi_2Te_3) is the most Common material used today (Kim and Hyun, 2000; Nolas et al., 1995).

In conventional compressor type refrigerator systems, the cooling medium is liquid or gas. This cooling medium acts as the carrier of the heat from the cold side of the heat exchanger to the hot side. In the case of thermoelectric cooling systems, the carrier of the heat is the electrons of the current flowing through the module. The amount of heat that is being pumped is directly related to the amount of electrons that passes through the p-n junctions, whilst the amount of electrons is determined by the current (Chang et al., 2007).

A thermoelectric module consists of p-n material junctions. The charge carriers in p-material are holes and in n-material, it is electrons. Only when a voltage is applied over the material the free electrons of the n-material will move in the conduction band and this movement of the free electrons are known as electron motion. On the other hand, holes in the p-material move in the valence band in the opposite direction as electrons and this is known as hole transfer. The movement of the hole is related to the energy levels in the valence band that is not occupied by the electrons (Kim and Hyun, 2000; Riffat et al., 2001; Von Cube and Steimle, 1981).

When voltage is applied to a p-n material junction and the current flows from the n-material to the p-material, a continuous recombination process takes place between the holes and the electrons. The conduction band in the n-material has a higher energy level than the valence band in the p-material. When the electron moves from the n-material (higher energy level) to the p-material (lower energy level) an amount of energy is released in the form of heat. This causes the one side of the thermoelectric module to get hot. When the electron moves from the p-material (lower energy level) to the n-material (higher energy level) an amount of energy is absorbed in the form of heat, because additional energy is required for the electron to move to a higher energy level. This causes the one side of the thermoelectric module to get cold. In this way, a heat pump is created to pump heat from the cold side of the module to the hot side (Riffat et al., 2001; Von Cube and Steimle, 1981).

INSTALLATION DESIGN OF THERMOELECTRIC COOLING MODULES (TECMs)

The installation design of a TECM as a heat pump is straight forward, but in order to use a TECM as a high efficient heat pump is a more complex installation. This part of the work provides a review on the factors required to ensure a high efficient TECM heat pump installation.

Determination of hot surface temperature of thermoelectric cooling modules (TECM)

On the hot surface of the TECM, a large heat sink is used to dissipate the heat that the TECM has to pump and the internal heat generated by the TECM itself. This heat is dissipated by the heat sink to the ambient air (Riffat et al., 2001). The temperature of the heat sink is therefore warmer than the ambient temperature. It is therefore important to keep the heat sink temperature as close as possible to the ambient temperature. A heat sink has a thermal resistance and it is defined as the amount of temperature that the hot surface rises above the ambient temperature for every watt that the heat sink dissipates (Rowe, 2000). The hot surface temperature of the TECM can thus be determined by multiplying the heat sink's thermal resistance with the power dissipated at the hot surface.

There is three ways of extracting the heat at the hot surface of the TECM. These include a heat sink with natural convection (no fan), heat sink with forced convection (fan included) and liquid cooling with forced convection. A heat sink with natural convection has a temperature rise of 2°C/W to 0.5°C/W. On the other hand, a heat sink with forced convection has a temperature rise of 0.5°C/W to 0.02°C/W. Liquid cooling has a temperature rise of 0.02°C/W to 0.005°C/W. In order to ensure reliability the hot surface temperature of the TECM must be kept below 85°C (Riffat and Xiaoli, 2003).

Thermal interface material (TIM) is a key component in the majority of power electronic systems. Heat generated by the TECM has to be transferred to a heat sink and finally dissipated to the ambient air. More detail on the thermal conductance between the junctions in presented in "thermal conductance between the junctions" part of this work.

Determination of cold surface temperature of thermoelectric cooling modules (TECM)

An important factor is the required temperature at the cold surface of the TECM. It is necessary to verify if a single stage TECM could be used to meet the temperature requirements. In the case where very low cold side temperatures are required the use of double or triple stage TECMs is prescribed (Hone, 1998). The amount of heat that is pumped at the cold surface of the TECM is calculated with the following equation (Chein and Chen, 1995):

$$Q_c = \alpha I T_c - \frac{I^2 \rho}{2G} - \boldsymbol{X}.\Delta T.G \qquad (1)$$

Where α is the Seebeck coefficient. (volts/°K), ρ is the resistivity. (Ω/cm), X is the thermal conductivity (watt/cm. °K) and G is the geometry value [(area of p-n blocks)/(length of p-n blocks)].

In order to reach colder temperatures a multi-stage or multi-tiered TECM approach can be used. It should

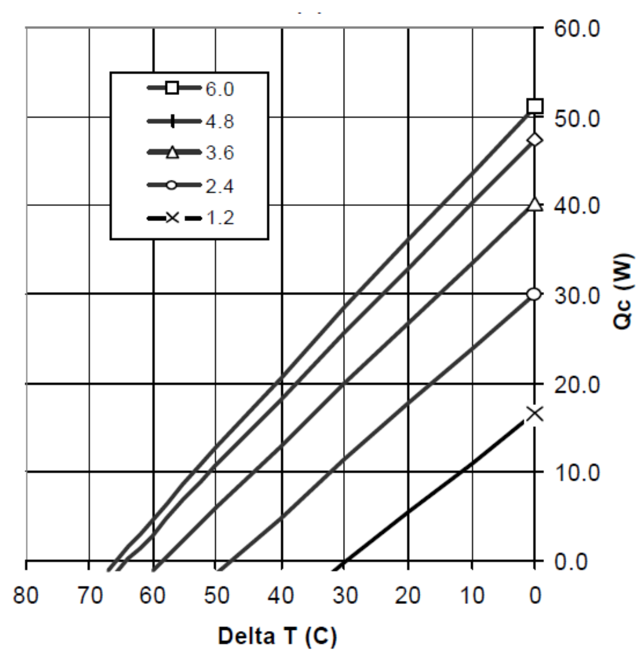

Figure 1. Heat pumped (Q_{max}) against temperature difference (ΔT) (Melcor, 1985).

however be noted that even though multi-stage or multi-tiered TECMs can achieve greater ΔT's, they have much less cooling capacity than their single-stage counterparts and are far more expensive to produce. More detail on cascades TECMs is presented in "temperature difference over TECM" part of this work.

Thermoelectric cooling module (TECM) power supply

A DC source, battery or photovoltaic panel can be directly connected as a power source on the TECM. In the case where a photovoltaic panel, battery or DC source is not available and the AC current is rectified to DC current, it should be kept in mind that the power ripple should be less than 10%. The more ripples there are in the input power, the less efficient the heat pumped will be, since the internal components experience a lot of Joule heating (Melcor, 1985). The deprivation caused by the ripple can be determined the following equation (Melcor, 1985):

$$\frac{\Delta T}{\Delta T} = \frac{1}{1+N^2} \qquad (2)$$

Where N is the percentage ripple.

The maximum current for a TECM is calculated as follows (Melcor, 2012):

$$I_{max} = \frac{X.G}{\alpha}\left[\sqrt{(1 + 2.Z.T_h)} - 1\right] \qquad (3)$$

Where Z is the figure of merit (in the region of 350 × 10^{-3} K^{-1}) and T_h is the hot surface temperature. Various super-lattices and alloys of different materials and skutterudites have been researched to improve the figure of merit (Hone et al., 1998; Hsu et al., 2004; Poudel et al., 2008; Venkatasubramanian et al., 2001).

The optimum current (I_{OPT}) for a TECM is calculated as follow (Melcor, 2012):

$$I_{opt} = \frac{X.\Delta T.G[1+\sqrt{(1+Z.X)}]}{\alpha.X} \qquad (4)$$

The optimum current (I_{opt}) is derived from the point where the heat pumped at the cold surface of the TECM is equal to the heat internally generated by the TECM, because of the joule heating effect (I^2R) (Hunang et al., 2005).

The optimum voltage (V_{opt}) for a TECM is calculated as follow (Melcor, 1985):

$$V_{opt} = \frac{L\rho}{G} + \alpha.\Delta T \qquad (5)$$

The first part ($\frac{L\rho}{G}$) of the equation consist of the multiplication of the optimum current with the resistance of one p-n junction. The second part ($\alpha.\Delta T$) is the Seebeck voltage that is a result of the temperature difference between the p-n junction. The amount of thermocouples (N) must be taken into account when calculating the optimum voltage (V_{opt}) for the whole TECM (Melcor, 2012).

Heat sink for thermoelectric cooling module (TECMS)

The amount of heat dissipated by the TECMs need to be calculated before a heat sink can be selected. Figure 1 illustrate that the amount of heat pumped (Q_c) decreases as the temperature difference (ΔT) between the hot and cold surfaces increase. The equation for heat pumped by the TECM is provided by Equation 1. The difference in the lines in Figure 1 represent the maximum input current (I_{max}) of the TECM. The higher the maximum current, the higher the heat pumped (Q_c) by the TECM.

The design of the heat sink for the hot surface of the TECM should not only take the amount of heat that the TECM pump into consideration, but also the heat generated (I^2R) by the TECM itself. The following equation provides the maximum power dissipated by the heat sink:

$$P_{sink} = (I_{max} \; x \; V_{max}) + Q_{max} \qquad (6)$$

This calculated value provides is a good estimation and overdesign value to ensure that the heat sink used for the extraction of heat from the hot surface of the TECM is sufficient (Chein and Chen, 1995). The assembly technique for the TECM with the hot surface heat sink and cold surface sink is also an important and critical factor. The interfaces between the TECM itself and the object being cooled on the cold surface and the heat sink on the hot surface have thermal resistances (Rowe, 2000).

These thermal resistances affect the flow of heat and cold negatively. Every possible method of minimising these resistances should be considered. The most effective way of minimizing these resistances is by using thermal grease. The thickness of the grease should not exceed 25 µm with a tolerance of about 13 µm (Melcor, 1985).

THERMOELECTRIC COOLING MODULE (TECM) PERFORMANCE

The size limitation of a TECM and the joule heating effect are the two factors that make the TECM cooling second-rated when compared to compressor cooling systems. Melcor (2012) claim that TECMs can pump up to 200 W when the ΔT is zero. This provide a compact and reliable way of pumping heat without any moving part being present, while employing zero electromagnetic radiation and still operation under variable input power.

TECMs also do not make use of harmful gasses to operate. For these reasons, TECMs can be used for application where standard compressor systems cannot operate. This part of the work provides a review on the factors that influence the performance of TECMs. These factors include the Joule heating effect, the relatively low temperature difference between the hot and cold surfaces of the TECM and the thermal conductance between the p-n junctions (Min and Rowe, 1999).

Joule heating effect

The amount of heat that is pumped at the cold surface of the TECM is calculated by means of Equation 1. In Equation 1, the total amount of heat pumped (P_T) is calculated by means the following equation (Chein and Chen, 2005; Hunang et al., 2005):

$$P_T = \alpha I T_c = \frac{V}{^{\circ}K} I\,^{\circ}K = V.I \quad (7)$$

The internal joule heating (P) caused by the resistive components inside the TECM is calculate by (Hunang et al., 2005):

$$P = \frac{I^2 \rho}{2G} = \frac{I^2 R}{2} \quad (8)$$

The amount of heat flow (P) between the cold and hot surface of the TECM is calculated by (Chein and Chen, 2005; Hunang et al., 2005):

$$\boldsymbol{P} = \boldsymbol{X}.\Delta T.G = \frac{W}{cm.^{\circ}K}.cm.\,^{\circ}K \quad (9)$$

The total amount of heat pumped at the cold surface (Q_c) of the TECM can be calculated by subtracting the internal Joule heating component and heat flow component from the total heat pumped by the TECM. The amount of heat that is pumped at the cold surface of the TECM is therefore lower, because of the internal Joule heating effect and the heat flow between the p-n junctions. Figure 2 provides the influence of the internal Joule heating effect and the heat flow between the p-n junctions on the heat pumping capability of the TECM (Melcor, 2012).

Temperature difference over thermoelectric cooling module (TECM)

The average range in which temperature differ between the hot and cold surface of a TECM is between 64 and 67˚C. In Figure 3, a compressor cooling system is compared to a TECM cooling system. The input power to both these systems is 60 W. Both systems pump 34 W of heat when the temperature difference (ΔT) between the hot and cold surfaces is 0˚C. This implies that the COP for both systems is the same at this point. As ΔT gradually increases, the heat pumping capability of the compressor system shows an advantage over the TECM system. The COP of the TECM system becomes less efficient than the compressor system with the increase in ΔT, because the compressor system has a much larger ΔT than the TECM system (Chein and Chen, 2005; Melcor, 2012).

There is however, a way to improve ΔT of a TECM system by means of cascaded TECMs. The ΔT of a cascaded TECM is significantly higher than that of a single stage TECM as, illustrated in Figure 4. With this gain in ΔT, there is however, one drawback, the heat pumping capability at 0°C becomes half of that of a single stage TECM. With the increase in ΔT the cascaded TECM become more superior to the single stage TECM. On the other hand, cascaded TECM systems cost four times the price of a single stage TECM system (Hone, 1998).

The power of the TECM greatly depends on the size of the TECM. TECMs can be cascaded or multi-staged together. The size of the complete cascaded TECM depends on the size of individual TECMs that are being cascaded.

The technology of TECMs has not yet reached the point where the resistance is zero at a high ΔT. When the resistance is zero, there will be no form of internal Joule heating and therefore the capability to pumped heat would be much higher (Hunang et al., 2005).

Thermal conductance between the junctions

During the steady state operation, the performance of Peltier cooling can be significantly improved by reducing

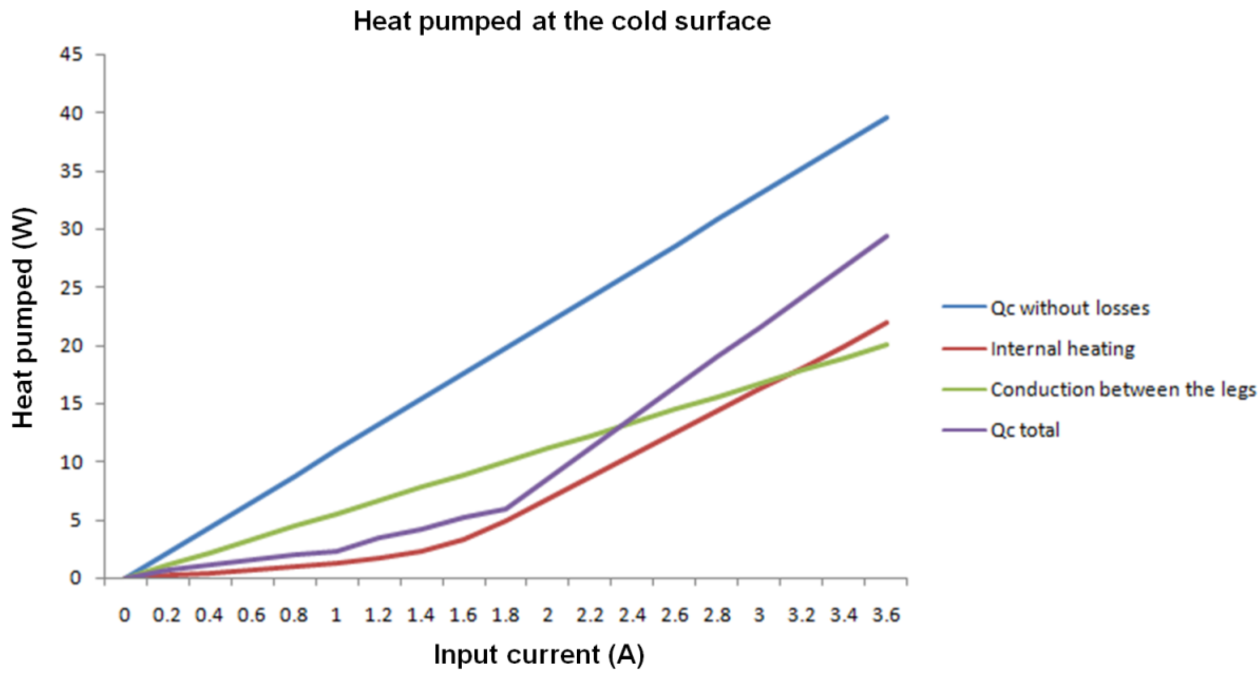

Figure 2. Actual heat pumped (Q_c) at the cold surface of the TECM (Melcor, 2012).

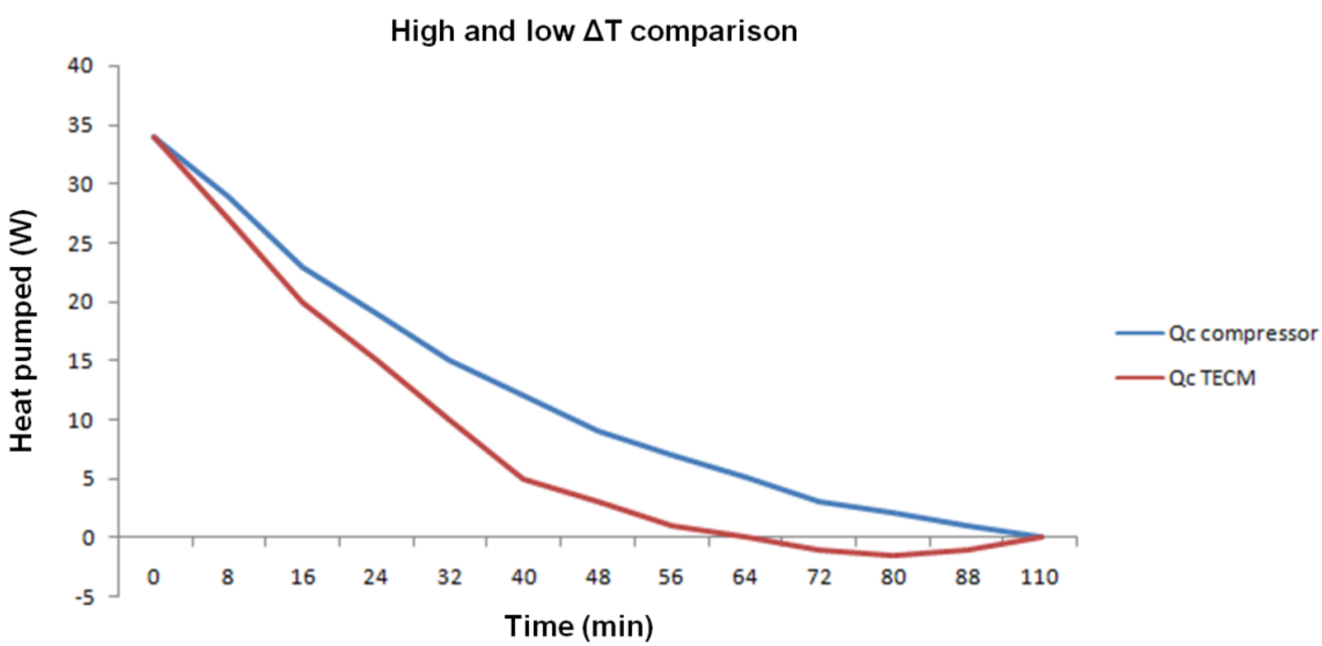

Figure 3. High and low temperature difference (*ΔT*) comparison (Melcor, 2012).

the thermal and electrical contact resistances. During transient cooling of hot spots the reduction of these resistances are even more crucial, since the values of these resistances are even higher. The figure of merit of thermoelectric modules can be increased by means of a high Seebeck coefficient, but the cooling capacity of the heat sink may become bottlenecked (Gupta et al., 2011).

Non-disruptive integration and low heat flux pumping capacity are additional challenges for TECM usage in electric coding applications. Thermal and electrical contact resistances further reduce the performance of these devices (Chowdhury et al., 2009). Ju (2008)

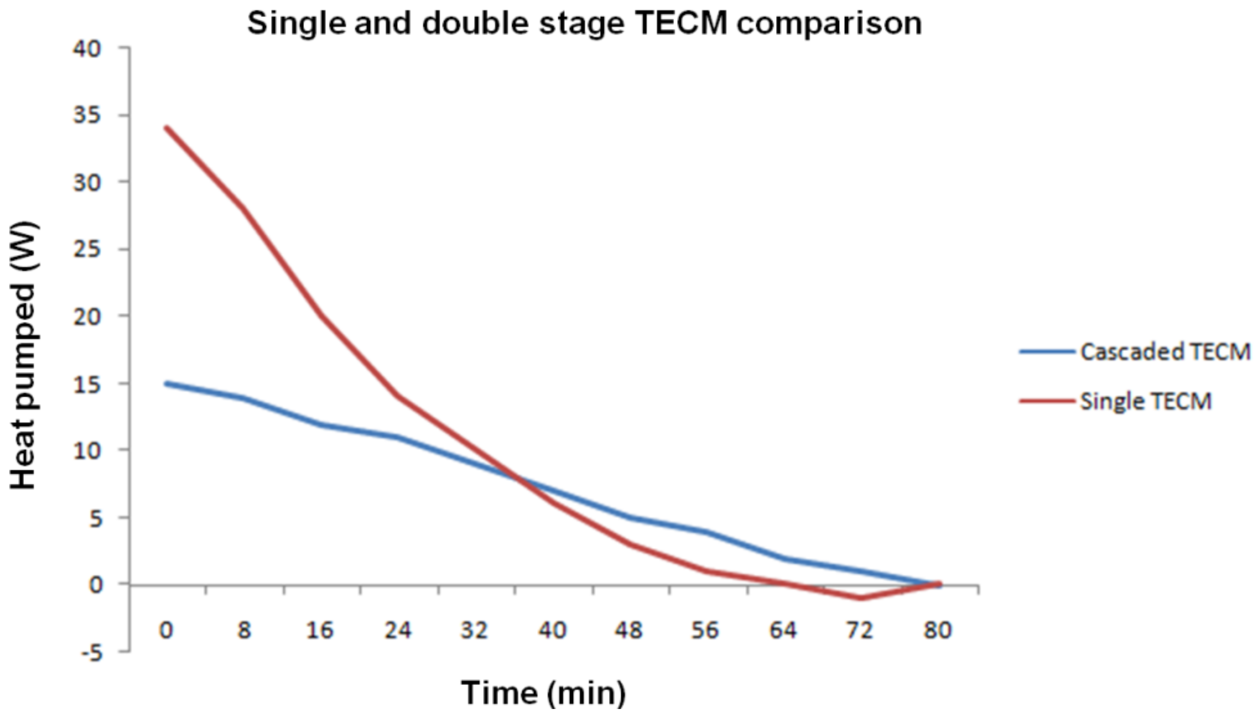

Figure 4. Single and double stage TECM comparison (Melcor, 2012).

Table 1. Comparing *ΔT*, Q_c and COP (Buist and Lau, 1996; Chein and Chen, 2005).

ΔT	Q_c	COP
5˚C	19 W	6.22
15˚C	15 W	1.64
25˚C	12 W	0.77

observed that electrical contact resistances cause the minimum achievable temperature at the cold junction to be influenced by the intense localized heating at the interface.

THERMOELECTRIC COOLING MODULE (TECM) EFFICIENCY

This part of the work provides a review on the factors (heat pumped, temperature difference, COP and TECM control) that influence the efficiency of the TECMs.

Heat pumped, Δt and coefficient of performance (COP)

The heat that is pumped at the cold surface of a TECM decrease exponentially when the temperature difference (*ΔT*) of the TECM increases. The change in *ΔT* also has an effect on the COP. It is shown in Table 1 that with an increase in *ΔT* the corresponding heat pumped (Q_c) and COP decrease. When the TECM is used in cooling application, the *ΔT* becomes smaller and the heat pumped (Q_c) and the COP becomes larger (Melcor, 2012).

The COP for a TECM is calculated by means of the following equation (Buist and Lau, 1996; Chein and Chen, 2005):

$$COP = \frac{Q_c}{I_{opt} \; .V_{opt}} \tag{10}$$

Where Q_c is the amount of heat that is pumped at the cold surface of the TECM and the optimum power input is calculated by the multiplication of I_{opt} and V_{opt}.

Thermoelectric cooling module (TECM) control

The use of an on/off cycle type temperature controller is not recommended for TECMs, since on/off cycle type temperature controller causes rapid expansion of the TECM's internal components, like the copper bars, as well as the heat sink's pressure variation, which causes the life span of the TECM to shorten (Güler and Ahiska, 2002). An option for a temperature controller is the proportional type temperature controller, because it regulates the increase and decrease in the current accurately and keeps the temperature constant (Huang and Duang, 2000).

The bandwidth of the thermal control however is an important element in the performance evaluation of the thermal sensation caused by the TECMs (Morimitsu and Katsura, 2011). The measurement of the bandwidth is difficult, since the heat transferred by the TECMs become nonlinear due to the effect of Joule heating (Morimitsu and Katsura, 2011). To overcome this problem, Morimitsu and Katsura (2011) proposed an observer-based temperature and heat inflow control system in which the nonlinear elements are compensated.

Deng et al. (2007) proposes temperature control of an aluminium plate with Peltier devices by using operator theory. In operator theory, the input space is mapped to the output space (Deng et al., 2004). Deng et al. (2007) shows that this method of temperature control has an influence on the effectiveness of the system. Harvey et al. (2007) suggested that distributed control of TECMs could result in a significant gain in terms of energy efficiency of the TECMs.

CONCLUSIONS

The exact calculation of the hot and cold surface temperatures of the TECM are crucial during the installation design phase of the TECMs, since these parameters provide the specifications for the required heat sink and power supply of the TECM. To optimally use TECMs as high efficient heat pumps the performance and efficiency of these modules must be taken into account. To maximize the performance of the TECMs, the Joule heating effect, difference between the hot and cold surfaces and thermal conductance between the p-n junctions must be optimized and to maximize the efficiency of the TECMs, the coefficient of performance and control must be optimized.

The factors that influence the performance of TECMs include the Joule heating effect, the relatively low temperature difference between the hot and cold surfaces of the TECM and the thermal conductance between the p-n junctions. The equations presented provide more detail to evaluate the performance of the TECMs. Figure 1 provides a comparison between the heat pumped (Q_{max}) in the TECM against the temperature difference (ΔT) in the TECM. The maximum input current (I_{max}) of the TECM is presented by means of different lines in the figure. The higher the maximum input current (I_{max}), the higher the heat pumped (Q_c) by the TECM.

It should be noted, that TECMs become less efficient at colder temperatures and the ratings for the temperature difference (ΔT) will be markedly reduced when you operate the TECM under extremely cold conditions. The reduction in the temperature difference (ΔT) has a direct influence on the amount of heat that can be pumped by the TECM, which results in a reduction in the performance of the TECM. There are therefore definite trade-offs between the heat being pumped by the TECM, the performance of the TECM and the efficiency of the TECM.

The characteristics of the TECM also depend on the application in which they are used in. The TECM will respond differently between applications that require low heat dissipation, compared to applications that require high heat dissipation.

Buist and Lau (1996) proposed a theoretical analysis on the enhancement of the thermoelectric cooling performance by means of high current electrical pulsing. According to Buist the enhancement is by virtue of the fact that Peltier cooling is a surface effect, whereas Joule heating is a volume effect. Peltier cooling is also concentrated at the cold junction, whereas Joule heating is a volume effect. Buist (1996) shows that enhancement is possible, but for only a short period. The application thereof will however be very limited.

Hodes (2012) shows that the performance and efficiency of a TECM is independent of the cross-sectional area of the pellets in the TECM, but the operating voltage can be adjusted to reduce DC-to-DC power conversion losses (Hodes, 2012). Yang et al. (2005) suggested that efficient pulsed coding could be achieved by choosing the pulse duration according to characteristic time constants.

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