Design and Investigation of Compressor-less Cooling System used for Automotive Application

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ABSTRACT : Automobile air-conditioning systems currently use liquid cooling approaches, R-134a. The systems require some mechanic components to support their operation, leading to highly cost of maintenance, installation and failure investigation. To alleviate, introducing cooling systems without mechanic movement become a challenge, where they can be applied to particular automotive domains such as bike, motorbike, etc. This paper thus introduces design and investigation of a compressor-less cooling system based on thermoelectric concept, peltier effect. The concept is suitable for designing the cooling system on automotive applications with the advantages of less mechanic movement, high reliability, small size, and light weight. The primitive investigation results illustrate that the minimum and maximum temperatures of the proposed system are at 16°C and at 25°C with power consumption at 38 watt and at 22 watt on DC voltage 12V, respectively. The design is continuously applied to lithium iron phosphate ($LiFePO_4$) battery capability at 20 ampere-hour(AH) within 6 hours.

Keywords : Peltier effect, Thermoelectric

1. Introduction

Thermoelectric module is a solid-state energy converter consisting of a bunch of thermocouples wired in series and thermally in parallel. In general, the module operates based on the concept of two heat sinks attached to its hot and cold sides in order to enhance heat transfer and system performance. Maximum coefficient of performance (COP) variation of a thermoelectric module under optimum current with fixed hot side temperature of 300 K is explained by Equ. (1) [1]

$$(COP)_{c,max} = \frac{T_c\sqrt{1+ZT_m} - \frac{T_h}{T_c}}{T_h - T_c\sqrt{1+ZT_m}+1}, \quad (1)$$

Where ZT_m is the thermoelectric material figure-of-merit at average hot side, T_h, and cold side, T_c, temperature, T_m. Based on the characteristic, the thermoelectric module provides advantages on high reliability, no mechanical moving parts, light weight, compact size and no operating fluid. Direct current (DC) electric sources such as photovoltaic (PV) cells, fuel cells and battery sources are directly applied to the module. Although high cost and low energy efficiency become its disadvantage, a particular system concerning on reliability, quiet operation and small operating area is taken into account [2].

With low COP, thermoelectric cooling has been restricted to particular applications, where COP is not as important as energy availability, reliability and quiet operation environment, such as space missions, scientific and medical equipment. However, as technology advanced, more and more new applications are emerging. Current thermoelectric cooling applications can be categorized into five application areas.

- ***Refrigeration market:*** there are two types of thermoelectric refrigeration devices: domestic and portable refrigerators. The major difference between these two is the availability of electrical power. Although the thermodynamic efficiency of a thermoelectric cooler is only 1% compared to 14% of stirling and reciprocating vapor compression refrigeration systems [3], thermoelectric refrigerators offer advantages such as a more ecological system, more silent and robust and more precise in temperature control [4]. The thermoelectric cooling devices are used for cooling small enclosures, such as domestic and portable refrigerator, portable icebox, beverage in cooler and picnic basket [5].

- ***Electronic applications:*** PC processors generate a huge amount of heat during operation coursed of reliable operation temperature on electronic components. In most cases, the maximum electronic device junction temperature needs to be held less than 85°C for reliable operation [6]. The maximum heat flow from a high performance electronic package is about 200 Watt and is still constantly increasing. Conventional passive cooling technologies using air or water as working fluid, such as the micro-channel sink, are unable to fully meet the heat dissipation requirement, thus active cooling methods become a solution. Thermoelectric coolers combined with air cooling or liquid cooling approaches at the hot side show great potential due to small size, high reliability and no noise.
- ***Attenuation heat dissipation:*** besides the applications discussed above, thermoelectric cooling has been applied to other occasions, such as generating fresh water [7], active building envelope system [8], photovoltaic-thermoelectric (PV-TE) hybrid module [9], and thermal management for high-power LEDs [10]. Photovoltaic (PV) modules suffer from elevated outdoor temperature which results in dropping efficiency. Researchers proposed using the thermal waste by attaching thermoelectric modules to the back of PV to form a photovoltaic-thermoelectric (PV-TE) hybrid module. Additional electricity can be generated through the thermoelectric module. Sark [122] found that this approach may lead to efficiency enhancement by up to 23% for roof integrated PV-TE modules using commercial available thermoelectric materials, while the annual energy yield would increase by 11%-14.7%. This application technically belongs to thermoelectric power generation. However, the thermoelectric module introduced here helps cool down the PV panels.
- ***Air-conditioning systems:*** thermoelectric domestic air conditioning systems are being competitive with vapor-compression counterparts. The actual COPs of vapor compression and thermoelectric air-conditioners are in the range from 2.6 to 3.0 and from 0.38 to 0.45 [11]. However, thermoelectric air conditioners have several advantageous features compared to their vapor-compression counterparts. For example, they

can be built into a planar structure simply handled on walls with offering a quiet operation environment especially suitable for household use. Cosnier et al. [12] presented an experimental and numerical study of a thermoelectric air-cooling and air-heating system. They have reached a cooling power of 50 Watt per module, with a COP between 1.5 and 2, by supplying an electrical intensity of 4A and maintaining 5°C temperature difference between the hot and cold sides. Gillott et al. [13] investigated thermoelectric cooling devices for small-scale space's conditioning application in buildings. A thermoelectric cooling unit was assembled and generated up to 220 Watt cooling capacity with a maximum COP of 0.46 under the input electrical current of 4.8A for each module.

- ***Automotive industry:*** most of automobile air conditioning systems currently use R-134a as refrigerant. The R-134a does not have ozone depleting effect but still faces the global warming effect. Leakage problem of the refrigerant in automobiles is more substantial than that in stationary air conditioners. Thermoelectric coolers have advantages of compact size, no moving parts and working fluid, compatible with automobile electrical system voltage, and easily switching between heating and cooling modes. Therefore, thermoelectric cooler appears to be especially favorable for automotive application. Yang and Stabler [14] presented a review on automotive applications of thermoelectric materials.

Thermoelectric cooling shows potential in other areas, such as domestic air-conditioning, integrating with solar PV. Cooling COP of thermoelectric refrigerators are generally in the range from 0.16 to 0.64 with a temperature difference around 20°C, depending on the performance of hot and cold side heat sinks. The major advantages of thermoelectric devices applied to electronic cooling are the compact size and large cooling density, which meets requirement of a single-chip package with heat dissipation rate of 250 Watt or even higher. The DC power need of thermoelectric device matches well with the automotive electric power supply. Integrating with automotive has been the best commercialized application.

2. State of the Art

Although vehicle customers are expecting high efficiency from vehicles, additional features for comfortability and convenience are competing demands [2]. Thermoelectric materials offer vehicle owners several unique features by providing heating and cooling for various items. Seats with thermoelectric heating and cooling are available today and have been in production for almost a decade in many luxury vehicles [15]. Cup holders maintaining hot and cold beverages are available on a few models. Small thermoelectric refrigerators are applied as features for limousines and recreational vehicles using 12V. Warmer cooler units are portable and localize in electrically anywhere based on the benefit of small, relatively light weight, and silent in operation. Their performance and efficiency are however relatively low; therefore there are many researchers considering on their improvement areas, material and system design.

- ***Customizing thermoelectric material specially for automotive application:*** Yang and Stabler [14] presented a review on automotive applications of thermoelectric materials. One of the novel approaches regarding thermoelectric materials is the phonon glass electron crystal (PGEC) [16] [17]. The basic idea is to significantly reduce phonon scattering, similar with glass. By introducing impurities into interstitial voids or cages of skutterudites or by forming distorted rock-salt layers between framework of CoO_2 triangle lattices of cobaltites, good electric conductivity is created to enhance the point-defect scattering or boundary scattering and to reduce the thermal conductivity. The nano route technique improving thermoelectric properties based on the effects of dimension was proposed by Hicks and Dresselhaus [18]. The effects of quantum-well and one-dimensional structures on the thermoelectric figure of merit with the assumption of parabolic bands and constant relaxation time in a one band material are examined. A. Ihring et al. [19] reported the investigation of the design, manufacturing, and characterization of a membrane-integrated thinfilm thermoelectric cooling arrangement to active temperature control and precise local cooling of the sensitive region in a thin-film dew-point sensor. To obtain a high performance concerning the maximum temperature decrease of the active-cooled membrane, a highly efficient thermoelectric materials combination of Sb and Bi0.87Sb0.13 was used for the fabrication of the in-plane Peltier configuration [20].

- ***System design and optimization:*** A completely new vehicle cabin design to incorporate with a distributed heating, ventilation and air-conditioning (HVAC) systems was difficult; however, it provided high potential to offer for the customer [21]. The design corresponded to the concept of fast cooling and heating, lower power requirements, heating or cooling only individual passengers, and better temperature control, especially for rear-seat passengers. Luo et al. [15] presented a novel thermoelectric air-conditioner for a truck cab. The COP factor of the cooling system was tested from the range of 0.4 to 0.8 under ambient temperature from 46°C to 30°C. They also found that the cooling performance can be further improved by optimizing system design and manufacture craft. Besides the automobile air-conditioning system, researchers also utilized thermoelectric device to control car-seat temperature. Hyeung-Sik et al. [22] developed a temperature-controlled car seat system utilizing thermoelectric device to either cooling down or heating up the car-seat. The control scheme was implemented by using a one-chip microprocessor, and the performance of device validated by experiments.

From the previous literature, there are two domains of enhancing and applying the thermoelectric devices to automotive application, i.e. 1) customizing thermoelectric material, 2) system design and optimization. This paper has considered on the second domain, where the particular design and optimization of cooling system specific for automotive are focused. The rest of this paper is organized as follows: the conceptual design and implementation is introduced in section III. The testing and investigation results are illustrated in section IV. The conclusion and future works are described in sections V and VI.

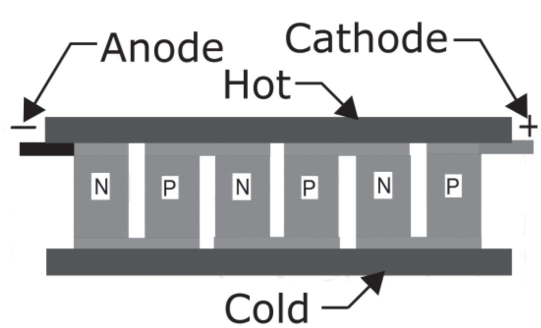


Fig. 1: Thermoelectric structure consisting of the PN-type semiconductors.

3. Conceptual Design and Implementation

Since the main purpose of the peltier-based cooling system is to invent the portable cooling device, its conceptual design and implementation are focused on portability, scalability, simple-to-use, and low power consumption. To conform to the concept, a chamber 1ft.3 operating with the existing peltier module, TES1-12702, where its maximum input voltage and current as well as its dimension are at 12V, 2A, and 30mmx30mm, is introduced as an exemplar. The 8-bit microcontroller is applied to control the cooling system based on the generic PID mechanism. The peltier phenomenon, the system design concept, and the implementation of the cooling system are thus described in this section.

3.1 Peltier Effect

Peltier phenomenon describes the processes occurring at the junction of two different conducting materials, PN-type semiconductor, in the presence of a flowing electrical current as shown in Fig. 1. Depending on the direction of current flow, the junction absorbs or dissipates heat to the surroundings. The heat power associated with the peltier phenomenon, Qp, can be performed as Equ. (2) [23].

$$Q_p = (\tau_P - \tau_N)I, \quad (2)$$

where *I* is the electrical current flowing in the thermoelectric module, P and N are the peltier coefficient of the PN-type semiconductors. The COP of the peltier phenomenon can be calculated as Equ. (1). From Equ. (2), the hot and cold temperatures on both sides of a peltier device are increased and reduced directly proportional to increasing the electrical current.

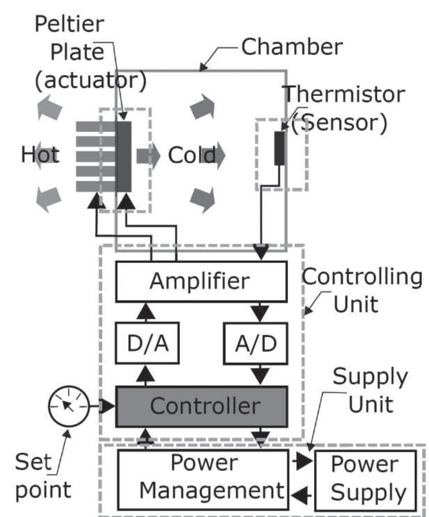


Fig. 2: Block diagram of the proposed peltier-based cooling system.

3.2 Design

According to the main purpose, the portability scalability, simple-to-use, and low power consumption are applied for the system design. The block diagram of the proposed peltier-based cooling system is shown in Fig. 2. There are four main modules on the system working as following concepts.

1) ***Controlling unit:*** the 8-bit microprocessor with low power functionality at runtime is selected. In Idle state, it is waiting for input set point information. As soon as, the input set point has been changed, the output signal calculated by the microprocessor is sent to the actuator unit, the peltier module.
2) ***Actuator unit:*** the perltier module is obtained as the system's actuator, where the generated hot and cold airs are proportional to input current. However, the design should consider on the potentiality of the used peltier module, where over voltage and current course of the peltier's damage. In addition, the unattended design on the power dissipation management at runtime degrades the efficiency of the peltier module.
3) ***Sensor unit:*** the digital temperature sensor is used to measure the cold temperature of the chamber, where its output information is sent to the controlling unit for calculation. As soon as, the new set point is valid, the system will be adapted by the controlling unit, where its output signal is continuously sent to the actuator unit to simultaneously generate both hot and cold air. The system still executes, as long as the detected temperature is not convergence to the set point temperature.
4) ***Power supply unit:*** the concept of the power supply unit is to economize power at 12V with the limited current at 2A, where the performance and efficiency of the system are acceptable. Thus, this unit should detect the voltage and current of the power source in real-time, specially applying to automotive application.

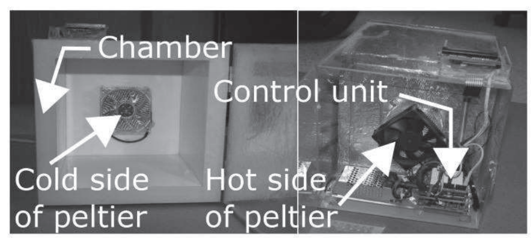


Fig. 3: Implementation of the peltier-based cooling system, 1ft.^{3}.

3.3 Implementation

The implementation of the peltier-based cooling system conforming to the block diagram in Fig. 2 is illustrated in Fig. 3. Scalability conceptual design is taken into account the system can be extended according to requirement and application. The exemplar consists of 1) a chamber 1 ft.^{3}, 2) a controlling unit, and 3) a peltier device. The hot and cold air are transferred through two DC fans attached with two heat sinks which are installed outside and inside the chamber. The 8-bit microcontroller, PIC18F4550, is applied for manipulation based on the PID adaptive controlling mechanism. At runtime, the controlling unit obtains a real-time digitally temperature from a sensor. The output signal which is calculated by the controlling unit corresponding to a set point is then generated to adapt the input current of the peltier device.

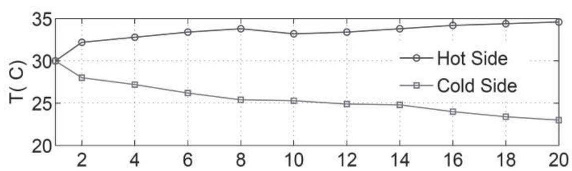


Fig. 4: Efficiency of the peltier device, TES1-12702, at the ambient temperature 30°C from 1min. to 20 min.

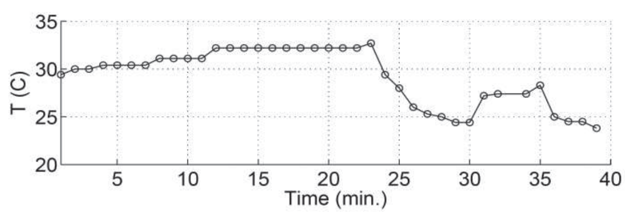
Table 1 The power dissipation of the thermoelectric device

Test	Targeted Consumed	Temp.(°C) Power(Watt)
1	16	38.28
2	20-23	27.56
3	21-24	24.13
4	22-25	21.92

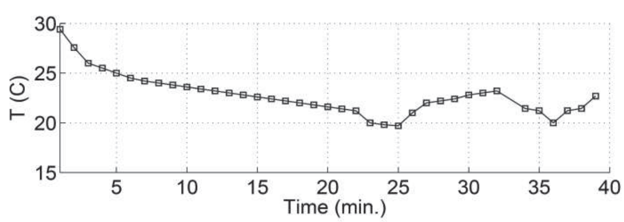
4. Testing and Investigation Results

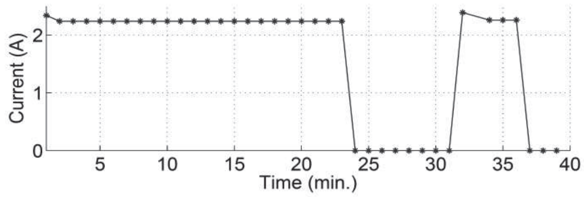
The consumed power on several targeted temperatures of the proposed compressor-less cooling system is illustrated in table I, where the peltier TES1-12702 with voltage at 12V and its resistance at 6Ω is applied. Fig. 4 shows the efficiency of the peltier device at the ambient temperature 30°C from 1 min to 20 min. From the figure, the decreasing and increasing rate temperatures of the cold and hot sides of the peltier module is at 0.4 and at 0.2. With the ration, we can summarize that the cold temperature is able to be efficiently generated by the peltier module.

(a) The temperature on the hot side

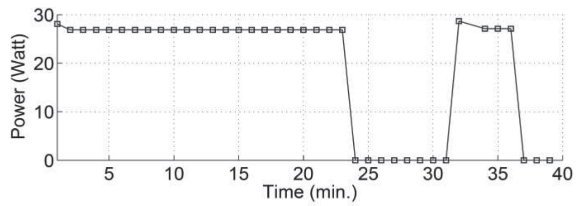


(b) The temperature on the cold side





(c) The consumed current



(d) The power dissipation

Fig. 5: Efficient investigation of the proposed cooling system based on the thermoelectric device at a constant input voltage 12V_{dc}.

The efficient investigation of the proposed cooling system based on the thermoelectric device at a constant input voltage 12V_{dc} is illustrated in Fig. 5. The dynamically change on the hot and cold sides of the peltier module during updating the set point is illustrated in Fig. 5a and 5b. The current and power dissipation of the peltier module are depicted in Fig. 5c and 5d. From the figures, the current and power are closed to the zero when the current set point is higher than the previous one. The power dissipation of the thermoelectric device on several targeted temperatures is depicted in Table I. From the table, the maximum consumed power is at 38.28 watt with the cold temperature at 16°C. Simultaneously, the system has been applied with a lithium iron phosphate ($LiFePO_4$) battery capability, 20 ampere-hour (AH). The investigation result shows that the system is able to work with the battery for 6 hours.

5. Conclusion

This paper proposed the design and investigation of a compressor-less cooling system based on thermoelectric concept, peltier effect. The system is designed conforming to portability, scalability, simple-to-use, and low power consumption concepts. The chamber 1ft.^{3} operating with the existing peltier module, TES1-12702, where its maximum input voltage and current as well as its dimension are at 12V, 2A, and 3030mm, is introduced as the exemplar which consists of four main units, i.e., 1) the controlling unit, 2) the actuator unit, 3) the senor unit, and 4) the power supply unit. The investigation results illustrate that the decreasing and increasing rate temperatures of the cold and hot sides of the peltier module is at 0.4 and at 0.2. The minimum and maximum temperatures of the proposed system are at 16°C and at 25°C with power consumption at 38watt and at 22 watt on DC voltage 12V, respectively. Moreover, the design is continuously applied to lithium iron phosphate (LiFe PO_4) battery capability at 20 ampere-hour (AH) within 6 hours.

6. Future Works

From the investigation results, the possibility of applying the compressor-less cooling system to motorbikes becomes our future works, where the design is able to be operated with DC voltage system, 12V, supplied by the motorbike synchronously within a small certain capacity. Since the efficiency of the cooling system based on thermoelectric concept is actually lower than the conventional ones, the optimization with engineering system design is an importance issues to relieve the problem. In addition, the overall performance and efficiency of the system also are our investigating tasks while the installed motorbike is used in real practice, particularly its power dissipation at run-time.

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