Transactions on Computer Science and Intelligent Systems Research
ISSN: 2960-1800, eISSN: 2960-2238 | Volume 14
TPCEE 2026

Design and Testing of an Active-Cooling Safety Helmet Module Based on a TEC1-12706 Thermoelectric Cooler

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Abstract. Passive heat dissipation helmets currently used by workers in high-temperature environments cannot effectively dissipate the heat that builds up inside the helmet and, therefore, are prone to heat stress. To alleviate this problem, this paper proposes an active-cooling safety helmet module using a TEC1-12706 thermoelectric cooler (TEC), working on the Peltier phenomenon. Cool air is blown inwards and warm air is blown outwards, with heat sinks mounted on both sides and a single fan which provide lateral air flow, and an enclosed baffle to separate the flow of cold and warm air. Closed loop temperature control is achieved with a temperature sensor which allows automatic shutdown at 25 °C.Under 12 V DC, TEC surface temperatures reach 23.6 °C (cold) and 28.9 °C (hot), ΔT = 5.3 °C, and the in-helmet temperature drops from 30.5 °C ambient to 25.3 °C—a cooling of approximately 5.2 °C. The compact, low-voltage, vibration- and noise-free design provides a feasible solution for personal thermal protection of outdoor workers.

Keywords: Thermoelectric cooler (TEC); high-temperature environments; safety helmet; active-cooling safety helmet.

1. Introduction

In occupational settings such as building construction, electrical maintenance, and metallurgy, workers are required to wear safety helmets for extended periods. Conventional safety helmets have an enclosed shell, and the only ways to dissipate heat passively are via the gap between helmet liner and the shell, and ventilation holes, while, if they are used at high temperature, the temperature inside the helmet is very close or even higher than the outside ambient temperature, resulting in poor heat dissipation from the head and easy to cause heat stress problems such as heat stroke and reduced concentration, threatening the safety of the user and reducing the safety accident rate[1, 2]. Therefore, active cooling while maintaining personal protective performance is a critical concern in the area of personal thermal protection.

Compressor-free, refrigerant-free, small size and quick response are the main advantages of thermoelectric cooling, which is based on the Peltier effect. With continuous advances in thermoelectric materials and device technologies, it has provided a viable route to wearable personal cooling[3,4]. In recent years, related studies have emerged rapidly, and wearable thermoelectric devices have shown broad prospects in personal thermal management [5]. Some studies have combined thermoelectric modules with composite phase-change materials to develop helmet cooling patches capable of rapidly storing cooling capacity; thermophysical modeling and analysis of head thermoelectric cooling devices have also verified the feasibility of cooling; and the design of intelligent Peltier-module-based helmet cooling accessories has demonstrated the feasibility of engineering implementation [6-8]. In addition, studies have compared helmet thermal management strategies including ventilation, phase-change materials, and thermoelectric cooling. However, existing designs mostly rely on cold-side contact conduction, resulting in uneven cooling distribution, and pay insufficient attention to hot-side heat dissipation and closed-loop temperature control, leaving room for optimization in both cooling performance and energy consumption.

To address the above issues, this paper designs and constructs an active-cooling module for safety helmets centered on a TEC1-12706 thermoelectric cooler. Heat sinks are mounted on both the cold and hot sides, a single fan provides lateral airflow to both, and an enclosed baffle separates the cold

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and hot air channels, thereby delivering cool air into the helmet and exhausting warm air outward. A temperature sensor is also integrated so that the module automatically shuts off when the in-helmet temperature drops to 25 °C, forming a closed-loop "temperature sensing–start/stop" control. This paper first presents the cooling principle and chip selection, then describes the design and construction of the module, and finally analyzes and discusses the cooling performance and energy consumption based on temperature tests, providing a reference for the design of wearable personal cooling equipment.

2. Fundamental Principles and Component Selection

2.1. Working Principle of the Thermoelectric Cooler (TEC)

When a direct current flows through a thermocouple circuit composed of N-type and P-type semiconductors connected in series, the Peltier effect causes charge carriers to undergo a change in electric potential as they pass through the junctions, requiring heat exchange with the surroundings: at the cold side, electrons and holes absorb heat from the environment when crossing the junction, lowering the temperature of that side; at the hot side, an equal amount of energy is released, thereby continuously pumping heat from the cold side to the hot side. The Peltier heat absorbed per unit time at the cold side is:

$$Q_p = \alpha T_c I \tag{1}$$

Where α is the Seebeck coefficient, Tc is the absolute temperature of the cold side, and I is the operating current. Owing to Joule heating and heat leakage generated as the current passes through the semiconductors, the net cooling capacity at the cold side is:

$$Q_c = \alpha I T_c - ½I^2R - K(T_h - T_c \tag{2}$$

Where R is the total electrical resistance and K is the total thermal conductance. The Peltier cooling capacity increases with the current, but so does the joule heating, as indicated in Eq. (2), so there is an optimum operating current at which the Peltier cooling is maximum. The energy efficiency is expressed in terms of the coefficient of performance (COP):

$$\mathrm{COP} = Q_c / UI \tag{3}$$

Where the voltage across the TEC is U. The "heat sink + fan" combination was used on the hot side to increase the convective heat transfer and reduce the temperature on the hot side so that the cooling capacity and energy efficiency of the cold side can be increased, and the heat accumulation on the hot side is the main factor limiting the cooling capacity of the TEC.

2.2. Chip Selection: TEC1-12706 and Its Suitability for Safety Helmet Cooling

With a ceramic-substrate sandwich construction, TEC1-12706 is just a simple DC powered thermoelectric cooling module, with a clearly defined model designation: "1" represents a single-stage thermoelectric stack, "127" represents 127 N/P-type thermocouples connected in series, and "06" represents a stated current of 6 A [9]. Some of the main parameters of the module are: maximum cooling capacity Qcmax ≈ 53–55 W, maximum temperature difference ΔTmax > 59 °C, and the maximum current Imax = 6 A, etc. and module size 40 mm × 40 mm × 4 mm. A lithium battery can be connected to the low voltage supply (12 V) for direct operation without the need to install an inverter circuit [10]. For safety helmet applications it has the following benefits: (1) small size (the side length is 40 mm, which can be attached to the inner wall of the helmet shell); (2) low voltage battery operation (12 V), suitable for situations where there is no external power supply; (3) no moving parts, no vibration or noise during operation; (4) the cooling capacity can be adjusted, which also allows the helmet to be cooled by a closed cooling loop. As mentioned in section 2.1, the ΔTmax >

59 °C is well above the head cooling requirement of 10-15 °C. Furthermore, according to Eq. (2), the cooling capacity is constrained by heat accumulation at the hot side; therefore, in practical application the hot side must be equipped with a heat sink and fan, as detailed in Section 2.3.

2.3. Design Principle of the TEC Cooling Module for Safety Helmet Applications

The key to using a TEC for helmet cooling lies in delivering the cooling capacity generated by the thermoelectric chip to the wearer's head through air circulation [5]. This design is where the cooling module is mounted in the cavity between the helmet shell and the helmet liner, taking up no extra space in the wearer's head, and the cool air is provided through the gap between the top of the head and the helmet liner.

Structurally, the heat sinks are placed on both cold side and hot side and a fan is placed laterally so as to simultaneously blow air across both heat sinks. A sealed partition is used to split the air duct into two separate cold and hot air channels, so the air flow over the cold side heat sink is cooled and provided to the helmet as cool air, while the hot air flow from the hot side is removed by the airflow and exhausted out of the helmet, avoiding hot air re-circulation to counter the cooling effect[7].

A temperature sensor is positioned close to the chip to determine the in-helmet temperature in real time as a control. The system automatically stops working when the temperature drops to 25 °C to prevent overcooling and to save the battery, and it restarts when the temperature returns to a higher level to maintain a closed-loop "temperature sensing–on/off" control, similar to the control strategy for existing helmet cooling accessories based on Peltier refrigerators [8].

The design is illustrated in a schematic way in Fig. 1. The design, which is based on the principle of 'cold/hot zone separation, enhanced air cooling and closed loop temperature control,' takes into account cooling performance, wearing comfort and energy consumption. A detailed construction process and test results is described in Section 3.

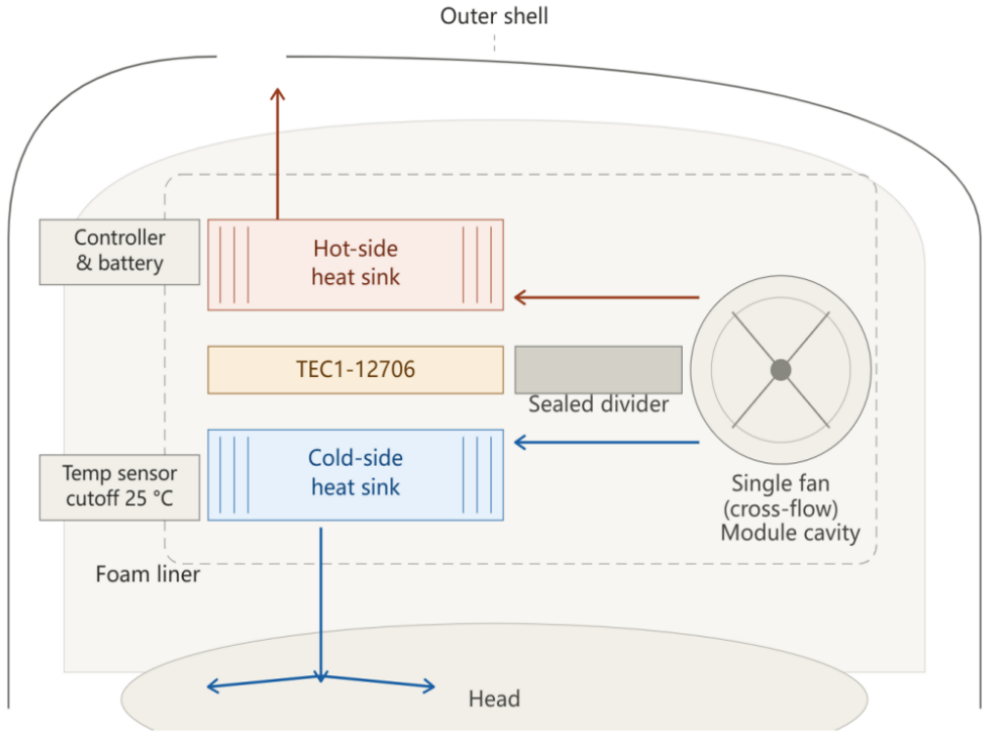

Fig. 1 Schematic diagram of the helmet structure. (Picture credit : Original)

3. Experimental Investigation

3.1. Experimental Setup and Method

In order to test the cooling performance of the module under real wearing conditions, the TEC1-12706 module was installed in the reserved cavity between the helmet shell and the foam liner, and a 12V DC supply was applied, as the fan and the TEC were switched on and off simultaneously. A digital temperature sensor (DS18B20) was used to measure the ambient temperature outside the helmet shell and another DS18B20 was attached to the inner side of the foam liner to measure the in-helmet temperature. In the interim, the TEC cold-side (front) and hot-side (back) temperatures were acquired from the TEC temperature acquisition interface (which came with the module), as shown in Fig. 2. The data were taken after reaching steady state (5 min running) and the data was averaged for three runs for each operating condition.

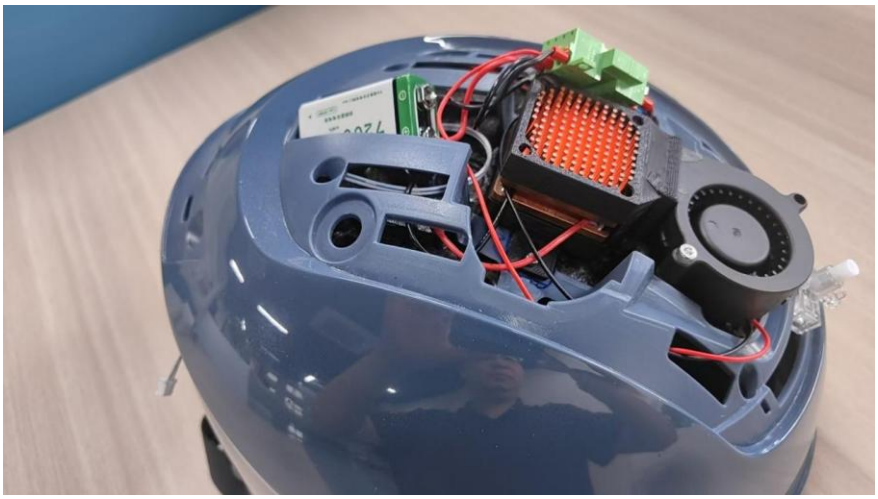

Fig. 2 Photograph of the cooling module installed in the helmet. (Picture credit : Original)

3.2. Evaluation Indicators

The measured surface temperatures of the TEC cold side and hot side were 23.6 °C and 28.9 °C, respectively, yielding a chip-level temperature difference of $\Delta T = 5.3$ °C (see Table 1). These results indicate that, under a 12 V supply, the TEC1-12706 successfully established a cooling effect, with the cold-side temperature dropping to near the human thermal comfort range. Given that the TEC1-12706 has a nominal maximum temperature difference of $\Delta T_{max} > 59$ °C and a maximum cooling capacity of approximately 53–55 W, the measured temperature difference is far below this limit, mainly owing to the following factors: (1) the confined internal space of the helmet and inadequate thermal isolation between the cold and hot air channels cause heat leakage (thermal cross-talk) losses; (2) a single fan blowing laterally across both sides simultaneously provides limited hot-side heat dissipation, resulting in an elevated hot-side temperature; (3) the actual operating current did not reach the rated maximum of 6 A, so the Peltier cooling capacity was not fully exploited; and (4) the head acts as a continuous heat source transferring heat to the cold side, thereby offsetting part of the cooling capacity.

Table 1. Measured cooling performance data.

Parameter	Value (°C)	Note
Cold-side surface temperature Tc	23.6	Front side of TEC
Hot-side surface temperature Th	28.9	Back side of TEC
TEC temperature difference ΔT_{TEC}	5.3	Th − Tc
Ambient temperature outside helmet Tout	30.5	Sensor 1
In-helmet temperature Tin	25.3	Sensor 2
In-helmet temperature reduction ΔT_{helm}	5.2	Tout − Tin

3.3. Directions for Improvement

Based on the above results, future optimization may focus on the following aspects: (1) adding thermal insulation material between the cold and hot air channels or extending the partition length to reduce heat leakage; (2) equipping the hot side with a heat sink of larger surface area or higher fin density, and increasing the fan speed to lower the hot-side temperature and enlarge the effective temperature difference; (3) introducing PWM current regulation into the control program to search for the optimal operating current within the 4–6 A range, balancing cooling capacity and energy efficiency; and (4) optimizing sensor placement by adding multi-point temperature measurement at locations such as the forehead and the crown of the head, so as to evaluate the in-helmet temperature distribution more comprehensively.

4. Conclusion

To address the problem of insufficient heat dissipation in safety helmets under high-temperature working conditions, this paper designed and constructed an active-cooling module based on the TEC1-12706 thermoelectric cooler. Directional heat transport can be achieved by the Peltier effect and the existence of an optimum operating current is determined by Joule heating and heat leakage. The 12 V low-voltage cooling, maximum cooling power of ~53–55 W and greater than 59 °C limit temperature difference make this chip ideal for use in small parts, like safety helmets. The design is based on the concept of "thermal zoning, forced-air cooling, and closed-loop temperature control": heat sinks are mounted on both the cold and hot side of the module, a single fan is used to provide lateral airflow, a sealed partition is used to separate the cold and hot air streams and the system automatically shuts off at 25 °C.

Under the 12V supply, measured cold-side temp is 23.6 °C with 5.3 °C chip temp difference, the in-helmet temp is measured to be 25.3 °C, which is 5.2 °C less than the hot-side temp, but this is not yet the nominal limit due to limitation in hot-side heat dissipation, thermal cross-talk between the air channels and heat transfer from the head. Future efforts could include the improvement of the hot-side heat dissipation, the improvement of the thermal isolation of the air channels, the optimization of the PWM current regulation, and multi-point temperature measurements/extended wear testing for validation. In this study, theoretical and practical reference for the design of wearable personal cooling equipment is provided.

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